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THESIS

EFFECT OF FIN HEIGHT ON FILM CONDENSATION OF STEAM ON STAINLESS STEEL INTEGRAL-FIN TUBES

by

George A. Incheck

March 1995

Thesis Advisor: Paul J. Marto

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EFFECT OF FIN HEIGHT ON FILM CONDENSATION OF STEAM ON STAINLESS STEEL INTEGRAL-FIN TUBES

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Lieutenant, United States Navy
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Submitted in partial fulfillment
of the requirements for the degree of

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NOMENCLATURE

A	cross-sectional area of tube, m^2
A_1	cross-sectional area of tube inlet end, m^2
A_2	cross-sectional area of tube outlet end, m^2
A_b	area of fin tip, m^2
A_{cond}	effective condensing surface for a rectangular fin tube, m^2
A_{eff}	effective surface area of tube, m^2
A_f	effective area of fin flank, m^2
A_{fin}	fin area, m^2
A_i	effective inside area of tube, m^2
A_o	effective outside condensing area of tube, m^2
A_s	horizontal tube area between fins, m^2
A_t	effective area of fin tip, m^2
b	intercept
C_i	leading coefficient of inside heat transfer correlation
C_o	leading coefficient of outside heat transfer correlation
C_p	specific heat, J/kg-K
D_{cond}	inside diameter of test condenser, m^2
D_{eq}	equivalent diameter of tube, m
D_f	outside diameter of finned tube, m
D_i	tube inside diameter, m
D_o	outside diameter of smooth tube, m
D_r	root diameter of tube, m
Emf	thermocouple or pressure transducer voltage, mV
F	ratio of gravity to shear force
f_f	fraction of fin flank blanked by condensate
f_r	rotameter flow rate, percent
f_s	fraction of interfin space blanked by condensate
f_v	volumetric flow rate
G	flow rate of condensate into interfin space, kg/s
g	local gravitational acceleration, 9.81 m/s

H	radial fin height, m
H_v	mean vertical fin height, m
h_b	heat transfer coefficient in flooded region, W/m^2-K
h_f	heat transfer coefficient on fin surface, W/m^2-K
h_{fg}	latent heat of vaporization, J/kg
h'_{fg}	latent heat of vaporization corrected for advection, J/kg
$h_{flooded}$	heat transfer coefficient for flooded section of tube, W/m^2-K
h_h	heat transfer coefficient for smooth tube surface, W/m^2-K
h_i	inside heat transfer coefficient, W/m^2-K
h_o	outside heat transfer coefficient, W/m^2-K
h_t	heat transfer coefficient on fin tips, W/m^2-K
$h_{unflooded}$	heat transfer coefficient for unflooded section of tube, W/m^2-K
Ja	Jacob number, $(C_p(T_{sat} - T_{wo})/h_{fg})$
K_1	as defined in equation (4.43)
K_2	as defined in equation (4.44)
k_{eff}	area averaged effective thermal conductivity over the fin height, W/m-K
k_c	thermal conductivity of coolant, W/m-K
k_f	thermal conductivity of condensate film, W/m-K
k_m	thermal conductivity of tube material, W/m-K
L	length of tube where condensation is occurring, m
$\bar{L}$	mean effective fin height, m
LMTD	log-mean-temperature-difference, °C
L_1	tube inlet length, m
L_2	tube outlet length, m
M	fin efficiency component
$\dot{M}$	total condensation rate on a tube
m	slope
m	mass, kg
$\dot{m}$	mass flow rate of coolant, kg/s

m_{air}	mass of noncondensibles, kg
m_{ij}	condensate flow rate in region ij, kg/s
m_{stm}	mass of steam, kg
n	number of data points
Nu	Nusselt number, (hD/k_f)
P	axial fin perimeter of tube, m
P_1	axial fin perimeter of tube inlet, m
P_2	axial fin perimeter of tube outlet, m
p	pressure, Pa
p_{air}	partial pressure of noncondensibles, KPa
p_{atm}	atmospheric pressure, KPa
p_{gage}	experimental pressure measured by gage, KPa
p_{sat}	saturation steam pressure, Pa
p_{stm}	partial pressure of steam, KPa
p_v	vapor pressure, Pa
p_{xdcr}	experimental pressure measured by transducer, KPa
Pr	Prandtl number, $(C_p\mu_c/k_c)$
Q	heat transfer rate, W
Q_{fin}	heat transfer rate from unflooded fin
Q_{flood}	heat transfer rate from the flooded fin tips
Q_{in}	electrical power to boiler heaters, W
Q_{int}	heat transfer rate from interfin space
Q_{loss}	heat loss of experimental apparatus, W
Q_{smooth}	heat transfer rate from a smooth tube
q''	heat flux, W/m^2
q_{flank}	heat flux from unflooded fin flank
q_{int}	heat flux from unflooded interfin space
q_{tip}	heat flux from unflooded fin tip
$q_{tip,flood}$	heat flux from flooded fin tip
R	boiler heater resistance, ohms
R_i	inside thermal resistance, K/W
R_o	outside thermal resistance, K/W
R_r	radius of tube measured to fin root, m
R_{total}	overall thermal resistance, K/W

R_w	tube wall thermal resistance, K/W
r_c	radius of curvature, m
Re	Reynolds number
$Re_{2\phi}$	two-phase Reynolds number
S_{xx}	as defined in equation (E.7)
s	interfin space length, m
T_1	coolant inlet temperature as measured by the quartz thermometer, °C
T_2	coolant outlet temperature as measured by the quartz thermometer, °C
T_b	temperature of fin base, °C
T_{cor}	coolant temperature rise due to viscous heating, °C
T_f	film temperature, °C
T_{in}	coolant inlet temperature, °C
T_m	mean coolant bulk temperature, °C
T_{out}	coolant outlet temperature, °C
T_{sat}	saturated steam temperature, °C
$T_{tip,flood}$	temperature of flooded fin tip, °C
T_{wo}	outside tube wall temperature, °C
t	fin thickness, m
$t_{\alpha/2,n-2}$	t-distribution statistic
U_o	overall heat transfer coefficient, W/m^2-K
U_∞	steam vapor velocity, m/s
u	uncertainty
V	boiler heater voltage, V
$V_{f,air}$	volume fraction of noncondensible gases
$V_{f,stm}$	volume fraction of steam
v_w	average coolant velocity, m/s
W	weight, lbf
$\overline{x}$	mean value of x
$\overline{y}$	mean value of y
Z	outside heat transfer correlation
α	confidence interval
B_1	empirically determined constant in equation (2.47)

B_{flank}	empirically determined constant in equation (2.46)
B_{int}	empirically determined constant in equation (2.47)
B_{tip}	empirically determined constant in equation (2.45)
γ	as defined in equation (4.42)
ΔT_{film}	temperature drop across condensate film, °C
ΔT_{flank}	vapor to fin flank temperature difference, °C
ΔT_{int}	vapor to interfin space temperature difference, °C
ΔT_{tip}	vapor to fin tip temperature difference, °C
$\epsilon_{\Delta T}$	heat transfer enhancement
$\zeta(\phi)$	condensate film thickness, m
η_f	fin efficiency
κ_1	weighting coefficient in equation (2.38)
κ_2	weighting coefficient in equation (2.38)
μ_c	coolant viscosity evaluated at T_m, kg/m-s
μ_f	condensate film viscosity, kg/m-s
μ_w	coolant viscosity evaluated a wall temperature, kg/m-s
ξ	"active" area enhancement
ξ_W	weighted "active" area enhancement
ρ	coolant density, kg/m^3
ρ_f	condensate film density, kg/m^3
ρ_{stm}	density of saturated steam, kg/m^3
ρ_v	vapor density, kg/m^3
Σ	summation expression
σ_f	condensate film surface tension, N/m
$\hat{\sigma}^2$	unbiased estimator of variance
ϕ_f	condensate flooding angle measure from top of tube
Ω	inside heat transfer correlation

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Lastly, I want to extend my greatest appreciation and love to my wife, Sara, whose support made my work possible. I also want to thank my four-year-old daughter, Laura, who despite her young age, helped repipe the PVC cooling water line in the test apparatus.

I. INTRODUCTION

A. BACKGROUND

The post-Cold War U.S. Navy has faced severe budgetary pressures with a consequent loss of shipbuilding and repair monies. Construction and operating costs are proportional to ship size. Any increase in equipment efficiency allows a reduction in component size and weight and lowers the overall cost. A majority of the steam propelled surface combatants with their large steam condensers have been replaced with the smaller, more efficient gas turbine powered vessels. Nevertheless, main engine condensers are still required on the older auxiliary ships, amphibious ships, and nuclear-powered vessels. Many condensers are also needed for the auxiliary equipment on all warships regardless of the method of propulsion.

One of the methods to improve the efficiency of condensers is to add fins to the tubes. Fins increase the surface area exposed to the vapor and would normally be expected to enhance condensation. Ideally, finned condenser tubes would be made from materials with high thermal conductivity to obtain higher heat transfer rates. Unfortunately, the saltwater operating environment of shipboard condensers requires that a higher priority be placed on corrosion protection. Titanium is a suggested material choice for use in saltwater applications. It is relatively light, yet strong, and best of all, it is extremely resistant to corrosion in the marine environment. Its disadvantages are high cost and relatively low thermal conductivity [Ref. 1]. The use of fins could offset these disadvantages by increasing the heat transfer rate and allowing a more compact and inexpensive design. However, there is very little experimental data available on the performance of low conductivity finned tubes. Since titanium and stainless steel have similar thermal conductivities (14.3 and 18.9 W/m^2-K respectively), experimental testing can be performed on stainless steel tubes as these are less expensive.

At the Naval Postgraduate School, Meyer [Ref. 2] explored the effects of fin height and tube thermal conductivity on the condensation of steam on integral rectangular finned tubes made from copper, aluminum, copper-nickel, and stainless steel for a range of fin heights from 0.5 to 1.5 mm. For the three higher thermal conductivity materials, increasing fin height was shown to enhance heat transfer as shown in Figure 1.1. The larger the thermal conductivity of the tube material, the larger was the rate of enhancement. These enhancements are greater than what would be expected from the increase in surface area from finning. Equally interesting, the lower conductivity stainless steel tubes showed an opposite trend. As fin height decreased, enhancement increased. Because the stainless steel enhancement curve must eventually decrease to one for a smooth tube, as the fin height continues to decrease, some optimum must exist at a fin height below that tested by Meyer [Ref. 2].

As a substitute for experimentation, many predictive theories are available to model condensation on finned tubes. They vary in complexity and assumptions and are suited for specific ranges of fluid properties and fin geometries. At present, no one model accurately accounts for all conditions. Models are important because they can provide numerical heat transfer data more quickly than costly experimentation. They are also suited for design optimization. Nevertheless, models still require extensive experimentation to validate their accuracy.

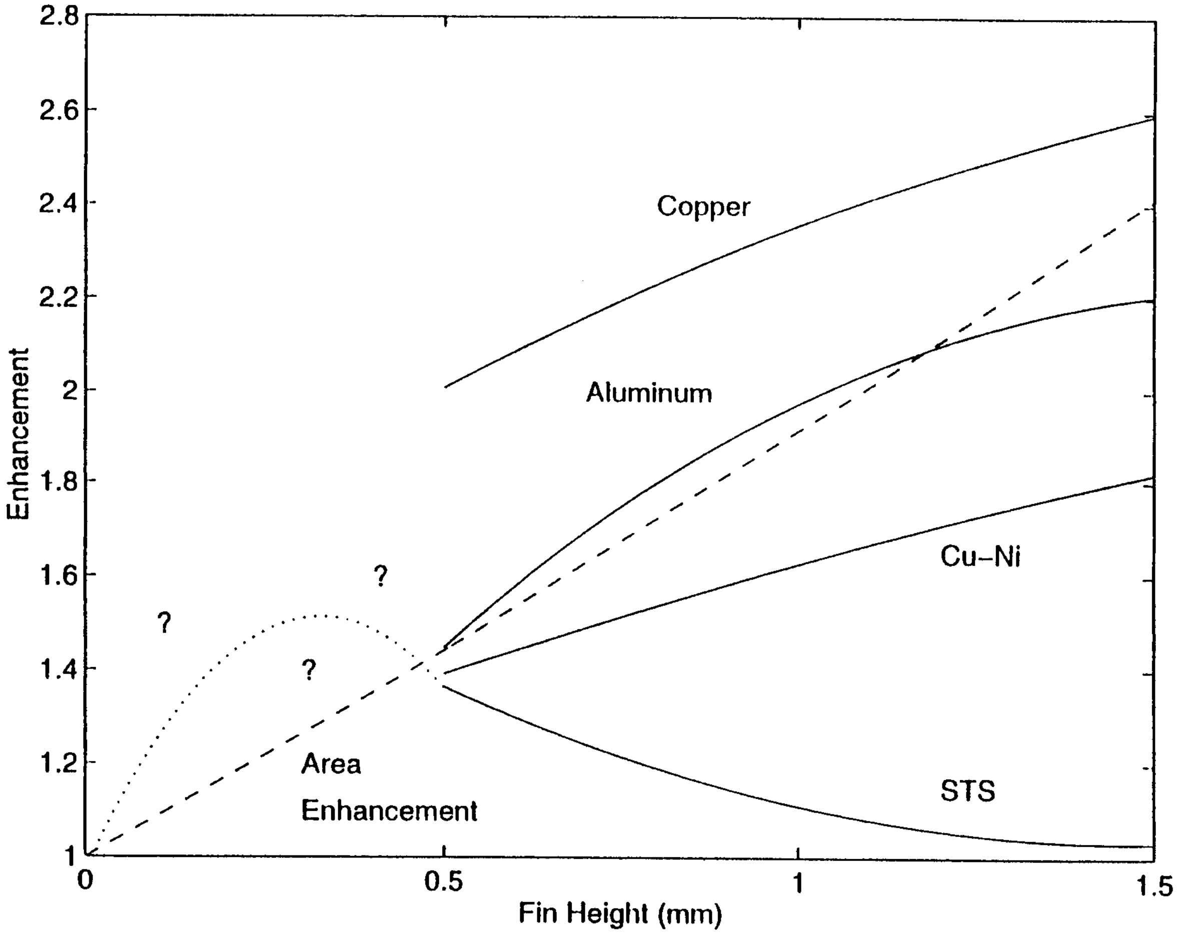

Figure 1.1. Meyer's [Ref. 2] Experimental Results for Enhancement vs. Fin Height for Copper, Aluminum, Copper-Nickel, and Stainless Steel Integral Fin Tubes Obtained at Atmospheric Pressure Conditions

B. OBJECTIVES

The main objectives of this thesis are therefore to:

1. Review the experimental procedures and data processing computer code of Meyer [Ref. 2] for validity.
2. Retest Meyer's stainless steel tubes and verify the trend of increasing enhancement for fin heights decreasing from 1.5 to 0.5 mm.
3. Test a set of new stainless steel tubes with fin heights ranging from 0.2 to 1.5 mm and experimentally determine any optimum fin height and corresponding enhancement.
4. Compare the experimental results with existing predictive models.

II. LITERATURE SURVEY

A. INTRODUCTION

Surface condensation occurs when a vapor is cooled below its saturation temperature by contacting a cold surface. Two types of surface condensation can take place -- filmwise and dropwise. In filmwise condensation, the condensate "wets" the surface with a continuous film, whereas in dropwise condensation, the condensate does not "wet" the surface, but forms droplets of various sizes instead. The drops form in imperfections on the surface and are then removed from the surface by gravity and/or vapor shear forces. Dropwise condensation results in much higher heat transfer coefficients (typically by an order of magnitude) than filmwise condensation because a portion of the cooled metal surface is directly exposed to the vapor [Ref. 3]. From a design perspective, a film condensation analysis is preferred as it gives a more conservative indication of condenser performance.

B. FILM CONDENSATION ON SMOOTH TUBES

When vapor condenses on smooth horizontal tubes in a filmwise mode, the condensate flows down by gravity and a continuous film always exists around the tube. The latent heat released by the condensing vapor is eventually absorbed by the cooling liquid that flows through the tube. The condensate film resists this heat flow because of its low thermal conductivity. This thermal resistance increases as the film thickness increases. At the top of the tube, the condensate film thickness and thermal resistance are small. Due to gravity drainage, the film thickness and thermal resistance increases with increasing distance around the perimeter of the tube.

Nusselt [Ref. 4] developed the foundation for the study of filmwise condensation on horizontal smooth tubes in 1916.

His formulation was done for a "quiescent" vapor condensing on a single horizontal tube. Due to the increase in the thickness of condensate as gravity draws it around the sides of the tube, the local heat transfer coefficient decreases around the tube circumference. Nusselt's theory for the average heat transfer coefficient around the tube accounts for the lower resistance at the top of the tube where the film thickness is minimum and the higher resistance at the bottom of the tube where the film thickness is maximum. The average outside heat transfer coefficient for the Nusselt theory is given by

$$h_o = 0.728\left[\frac{k_f^3 g \rho_f (\rho_f - \rho_v)\, h'_{fg}}{\mu_f D_o (T_{sat} - T_{wo})}\right]^{1/4} \qquad \textbf{(2.1)}$$

where h'_{fg} is the modified latent heat of vaporization that accounts for advection effects [Ref. 3]

$$h'_{fg} = h_{fg}(1+0.68Ja) = h_{fg}+0.68C_p(T_{sat}-T_{wo}), \qquad \textbf{(2.2)}$$

and the fluid properties are evaluated at the film temperature (T_f) given by

$$T_f = \frac{1}{3}T_{sat} + \frac{2}{3}T_{wo}. \qquad \textbf{(2.3)}$$

C. FILM CONDENSATION ON FINNED TUBES

When a horizontal finned tube comes in contact with a highly wetting condensate, surface tension drives the liquid from the fin tips and flanks to the fin root. This effect was first described in 1954 by Gregorig [Ref. 5]. For horizontal finned tubes, the liquid pressure at any point along the fin profile is given by

$$p = p_v + \frac{\sigma_f}{r_c}. \qquad \textbf{(2.4)}$$

At the top of a fin, the film has a convex appearance and the local pressure is greater than the vapor pressure due to a small radius of curvature. At the fin root, the film has a concave appearance, the radius of curvature is negative, and so the local liquid pressure is less than vapor pressure. The pressure difference between the fin tip and root causes the condensate to flow toward the fin root. As a result, the film thins near the fin tips and thickens near the root. The condensate from the fin tips and flanks flows into the interfin space. The film thickness in the interfin space increases along the circumference, and eventually, it completely fills the interfin space, so that the interfin is completely "flooded" with condensate.

Referring to Figure 2.1, the flooding angle (ϕ_f) is defined as the angle measured from the top of the tube to a point around the tube circumference where the condensate film between the fins just fills the entire interfin space. Along the bottom of the tube, the retained liquid extends past the fins. This portion of the flooded region is referred to as the drop-off zone and is estimated to be ten percent of the tube circumference [Ref. 7]. The flow of condensate between the fins depends on the ratio of the surface tension forces to the gravity forces since the former acts to retain the condensate between the fins while the latter acts to drain the condensate. Thus two competing mechanisms exist. Surface tension thins the condensate film along the fins in the "unflooded" region improving the heat transfer, but retards drainage, increasing the size of the "flooded" region, degrading the heat transfer. Yau et al. [Ref. 8] and Wanniarachchi et al. [Ref. 9] studied film condensation on finned tubes and observed that heat transfer enhancement was greater than what could be explained by increased surface area alone. This indicates that the beneficial effect of condensate thinning offsets the detrimental effect of

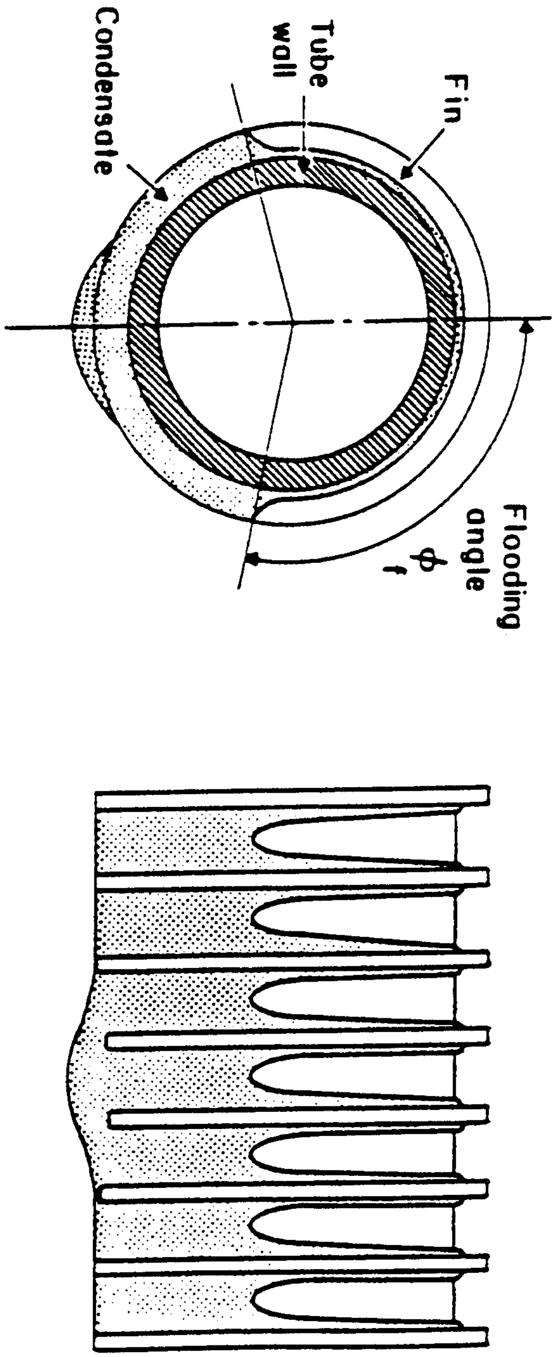

Figure 2.1. Schematic of Condensate Flooding Angle (ϕ_f) on Finned Tubes (illustrated in gray). From Ref. [6].

flooding.

Condensation on a finned tube is a complex phenomenon involving many variables. These include condensate flow characteristics, surface tension and gravity forces, wall and fin conduction effects, condensate film thickness variations, and vapor velocities [Ref. 9]. The accuracy of any predictive model is dependent on how closely it can account for these effects.

D. CONDENSATE RETENTION OR FLOODING ANGLE

In 1946, the first measurements of condensate retention were reported by Katz et al. [Ref. 10]. These measurements were made under static conditions (i.e., no condensation taking place) using water, aniline, acetone, and carbon tetrachloride. Fin heights of 1.2 to 5.7 mm, and fin densities of 276 to 984 fins per meter were used. Since the vapor density is much smaller than the condensate density, it was neglected. It was shown that as much as 100 percent of the tube surface could be flooded with retained condensate, depending mainly on the ratio of surface tension to condensate density and on the fin spacing. Katz's equation for the flooding angle is

$$\frac{\phi_f}{\sin\phi_f} = \frac{180}{980}\,\frac{\sigma_f}{\rho_f g}\left[\frac{4D_f - 2D_r + 2s}{\pi s\,(D_f^2 - D_r^2)/4}\right]. \qquad (2.5)$$

This equation shows a direct relationship between an increasing surface tension to condensate density ratio and an increasing flooding angle. For constant fin height and fin spacing, an increasing root diameter leads to a decreasing flooding angle.

In 1981, Rudy and Webb [Ref. 11] were the first to measure condensate flooding angles under both static and dynamic (condensation occurring) conditions and they concluded that the flooding angle did not differ significantly for the two cases. Honda et al. [Ref. 12] confirmed the conclusion of Rudy and Webb from a photographic study. Honda developed an expression for the flooding angle on rectangular fin tubes as

$$\phi_f = \cos^{-1}\left[\frac{4\sigma_f}{\rho_f g s D_f} - 1\right]. \qquad \textbf{(2.6)}$$

It is valid for interfin spacing less than or equal to twice the fin height ($s \leq 2H$). This equation was also independently determined by Rudy and Webb [Ref. 13] and Owen [Ref. 14] and confirmed from experimentation. Rudy and Webb noted that it predicted the flooding angle within ten percent for condensation of R-11, n-pentane, and water on 19 mm fin diameter tubes of 748 to 1,378 fpm. For horizontal tubes with interfin spacing greater than twice the fin height ($s > 2H$), Honda et al. [Ref. 15] and Masuda and Rose [Ref. 16] determined the flooding angle as

$$\phi_f = \cos^{-1}\left[\frac{16\sigma_f H}{\rho_f g D_f (s^2 + 4H^2)} - 1\right]. \qquad \textbf{(2.7)}$$

E. PREDICTIVE MODELS

1. Beatty and Katz

In 1948, Beatty and Katz [Ref. 17] developed a simple, analytical model to predict the average heat transfer coefficient for spiral integral fin tubes. They treated the interfin space of the tube as a horizontal smooth tube and the fin flanks as plain vertical surfaces. They combined Nusselt's expressions for each to model a finned tube. They accounted for the conduction effects through the fin by including fin efficiency. To simplify the problem, they assumed that the condensate was only gravity-drained and that there was no effect of surface tension in thinning the condensate film or in retaining the condensate between fins. For rectangular fins, their equation reduces to

$$h_o = 0.689\left[\frac{k_f^3 \rho_f^2 g h_{fg}}{\mu_f (T_{sat} - T_{wo})}\right]^{1/4}\left[\frac{1}{D_{eq}}\right]^{1/4}, \tag{2.8}$$

where the equivalent diameter of a finned tube (D_{eq}) is expressed by

$$\frac{1}{D_{eq}^{1/4}} = \eta_f\left(\frac{1.3A_f}{A_{eff}\overline{L}^{1/4}} + \frac{A_t}{A_{eff}D_f^{1/4}}\right) + \frac{A_s}{A_{eff}D_r^{1/4}}, \tag{2.9}$$

the mean effective fin height ($\overline{L}$) is

$$\overline{L} = \pi\frac{(D_f^2 - D_r^2)}{4D_f}, \tag{2.10}$$

the effective surface area (A_{eff}) is the sum of the effective surface areas of the fin and interfin space

$$A_{eff} = \eta_f A_{fin} + A_s, \tag{2.11}$$

the fin area (A_{fin}) is the sum of the flank area (A_f) and tip area (A_t)

$$A_{fin} = 2A_f + A_t = \frac{\pi(D_f^2 - D_r^2)}{2} + \pi D_f t, \tag{2.12}$$

and the horizontal tube area (A_s) is

$$A_s = \pi D_r s. \tag{2.13}$$

This was the first analytical model to predict the condensing heat transfer coefficient on a horizontal finned tube. The experimentally determined leading coefficient (0.689) is only five percent less than the theoretically derived constant (0.728) of the Nusselt analysis for a smooth tube. Equation (4.8) shows that the heat transfer coefficient decreases with increasing tube diameter. Since Beatty and Katz ignored surface tension, their model should perform more accurately for low surface tension fluids, such as refrigerants, and for tubes with low fin densities. Also, the model should perform better under higher pressures, and hence, higher saturation temperatures where surface tension is lower. In their experiments, Beatty and Katz only tested tubes with low fin densities and fluids with low surface tensions. Although the fins used by Beatty and Katz were spiral, their theory applies to rectangular-shaped annular fins as well.

2. Soviet Models

Between 1971 and 1977, Karkhu and Borovkov [Ref. 18] and Zozulya, et al. [Ref. 19] developed the first analysis which recognized the importance of surface tension on horizontal finned tubes. They demonstrated that surface tension forces could increase the condensation rate by 50 to 100 percent. They used Nusselt's assumptions on the mechanisms of heat transfer through a liquid film on a smooth surface, the differential equation of condensate motion that assumed gravity driven, laminar flow of condensate from the fin to the interfin space, and appropriate boundary conditions to solve for the thickness of the condensate film in the interfin space. They used film thickness, fluid properties, and fin geometry to determine the flow rate of condensate (G) into the interfin space. The one-dimensional conduction equation for the fin was solved to determine fin temperature distribution. Finally, using numerical methods to solve the resulting differential equations, they found an expression for the average heat transfer coefficient such that

$$h_o = \frac{G h_{fg}}{A_{cond}(T_{sat} - T_b)} \qquad \textbf{(2.14)}$$

where T_b is the temperature at the base of the fin and A_{cond} is the effective condensation surface for a rectangular fin and is given by

$$A_{cond} = \pi \frac{D_r}{2}\left(\frac{s+t}{2} + H\right). \tag{2.15}$$

They reported predictions within five percent of the experimental data for film condensation of steam and R-113 on brass and copper tubes with a fin spacing of 0.14 mm and 0.20 mm, respectively.

3. Rudy and Webb

In 1981, Rudy and Webb [Ref. 11] reported that the Beatty and Katz model overpredicted the heat transfer coefficient with increasing error for fin densities greater than 1,024 fpm and for fluids with surface tension to condensate density ratios greater than 30 x 10^{-6} N-m^2/kg. They proposed a possible improvement by applying equation (2.8) to the unflooded region only, assuming that heat transfer in the flooded portion was negligible. Because their equation was still based on a gravity-drained model and because it neglected any heat transfer through the flooded region, it underpredicted the average heat transfer coefficient of condensing R-11 by ten to fifty percent. They concluded that any experimental success that Beatty and Katz had was due to offsetting errors from the competing effects of surface tension. That is, the loss of heat transfer due to flooding cancelled out the gain in heat transfer from film thinning.

In 1982, Webb et al. [Ref. 20] confirmed the conclusions of the 1981 study. Judging a gravity-drained model as insufficient, they developed a new model which included surface tension effects. They modified the original Nusselt equation for a vertical plate so that surface tension causes the condensate to drain from the fin tip to the base and gravity causes the condensate to flow in the interfin space. They assumed a linear liquid pressure variation over the fin. They were able to predict the experimental results obtained from the condensation of R-12 on a plate with vertical fins to within ten percent.

Later, Rudy and Webb [Ref. 21] expanded this model to predict the heat transfer coefficient for rectangular radial fins. The Nusselt equation for horizontal tubes was used for the tube area between fins where

$$h_h = 0.725\left[\frac{k_f^3 \rho_f^2 g h_{fg}}{\mu_f D_r (T_{sat} - T_{wo})}\right]^{1/4}, \tag{2.16}$$

while the Nusselt equation for the fin surface was modified by replacing the body-force term (ρg) by an equivalent expression based on surface tension force yielding

$$h_f = 0.943\left[\frac{k_f^3 \rho_f h_{fg}}{\mu_f (T_{sat} - T_{wo})}\right]^{1/4}\left[\frac{2\sigma_f}{H^2}\left(\frac{1}{s} + \frac{1}{t}\right)\right]^{1/4}. \tag{2.17}$$

They assumed no heat transfer through the flooded region. Their resulting weighted area expression for the total heat transfer coefficient is

$$h_o = \frac{\phi_f}{\pi}\left(\frac{A_s}{A_b} h_h + \frac{\eta_f A_{fin}}{A_b} h_f\right) \tag{2.18}$$

where A_s and A_{fin} are defined previously and A_b is equal to the fin diameter of one fin pitch, i.e.

$$A_b = \pi D_r (s + t)\,. \tag{2.19}$$

This expression provided an accuracy of better than ten percent for condensation of R-11 on short, finely-spaced fins and was an improvement over Beatty and Katz. It overpredicted the heat transfer coefficient for other tubes by up to 25 percent. They attributed this to gravity induced drainage becoming more important as fin height and spacing increased. They concluded that their linear pressure gradient model is better than the Beatty and Katz gravity drainage model for predicting the heat transfer coefficients for fin densities greater than 1200 fpm and fin heights of less than 0.9 mm.

Still later, Webb et al. [Ref. 22] modified the previous model to allow for heat transfer in the flooded region. They assumed surface tension drainage from the fin, discarded the assumption of a linear surface tension induced pressure gradient, and used an analysis of Adamek [Ref. 23] to determine the film thickness on the fins in the unflooded region. Gravity drainage from the interfin region was assumed. Nusselt's equation for condensation on a smooth, horizontal tube was modified to account for the increase in film thickness due to drainage from the fins. The area weighted average heat transfer coefficient is then

$$h_o = \frac{\Phi_f}{\pi}\left(\frac{A_s}{A_b}h_h + \eta_f\frac{A_{fin}}{A_b}h_f\right) + \left(1 - \frac{\Phi_f}{\pi}\right)h_b \qquad \textbf{(2.20)}$$

where h_b is the heat transfer coefficient in the flooded region. The model predicted the heat transfer coefficient for condensation of R-11 on tubes with fin pitch of 748 to 1,378 within twenty percent. Heat transfer across the flooded region was shown to be minimal.

4. Owen

In 1983, Owen et al. [Ref. 14] also recognized the necessity of including the effects of condensate retention in heat transfer models. They demonstrated that the Rudy and Webb [Ref. 11] modification of Beatty and Katz that neglected heat transfer in the lower portion of the tube with retained condensate, underpredicted the heat transfer coefficient when a significant amount of condensate was retained between the fins. They sought a model that permitted heat flow through the condensate retained region. Like Rudy and Webb, they extended the Beatty and Katz model to include the flooding angle.

They considered the flooded and unflooded regions with condensation occurring on both the retained condensate and the fin tips. In the unflooded region, the Beatty and Katz equation was used so the heat transfer coefficient is

$$h_{unflooded} = 0.725\left[\frac{k_f^3 \rho_f^2 g h_{fg}}{\mu_f D_{eq}(T_{sat} - T_{wo})}\right]^{1/4} . \qquad \textbf{(2.21)}$$

In the flooded region where condensation occurs on the surface of the retained condensate and on the fin tips, the heat transfer coefficient is

$$h_{flooded} = \left(\frac{1}{h_t} + \frac{1}{h_h}\right)^{-1} . \qquad \textbf{(2.22)}$$

Here, h_h is the heat transfer coefficent arising from condensation on a plain tube of diameter $D_o = D_f$ given by

$$h_h = 0.725\left[\frac{k_f^3 \rho_f^2 g h_{fg}}{\mu_f D_f (T_{sat} - T_{wo})}\right]^{1/4} , \qquad \textbf{(2.23)}$$

and h_t is the heat transfer coefficient for the fin tips combined with the retained condensate region,

$$h_t = \frac{k_{eff}}{H} , \qquad \textbf{(2.24)}$$

and the area averaged effective thermal conductivity over the fin height (k_{eff}) is

$$k_{eff} = \left(\frac{1}{s+t}\right)(t k_m + s k_f) . \qquad \textbf{(2.25)}$$

The average heat transfer coefficient for the entire tube length having an effective area A_{eff} is thus an area average of the heat transfer coefficients for the upper and lower portions, or

$$h_o = \frac{\Phi_f}{\pi} h_{unflooded} + \left(1 - \frac{\Phi_f}{\pi}\right) h_{flooded}. \qquad \textbf{(2.26)}$$

Their model agreed within 30 percent of Beatty and Katz's experimental data for R-11, R-12, R-22, water, acetone, methyl chloride, n-pentane, sulfur dioxide, propane, and n-butane. This was little improvement over the Beatty and Katz model. They assumed it would be more accurate in situations where an appreciable fraction of the tube was covered with retained condensate. Honda and Nozu [Ref. 12] later showed that this model overpredicts steam data by up to a factor of two.

5. Honda

Between 1984 and 1987, Honda [Refs. 15, 24] developed an analytical model for film condensation on horizontal, low integral-fin tubes. The model is extremely complex and required a numerical solution, but is the most comprehensive available. It includes the effects of variable condensate film thickness along the fin, fin efficiency, gravity versus surface tension forces, and variable temperature between the fin root and interfin space. The model assumes that the wall temperature is uniform, condensate flow is laminar, condensate film thickness is small, and the dominant flow on the fin is in the radial direction. The equation for condensate flooding angle is generalized to include all fin heights and spacings.

The tube is divided into the flooded and unflooded regions and three cases are considered based on fin spacing and condensation rate. These are shown in Figure 2.2. These cases are used because it is expected that the depth of the condensate film in the interfin space would have a significant impact on the amount of heat transferred. The first case considers a small interfin spacing with a high condensation rate. The second considers a large interfin spacing with a low condensation rate where fin height is large relative to interfin spacing. The last considers a large interfin spacing

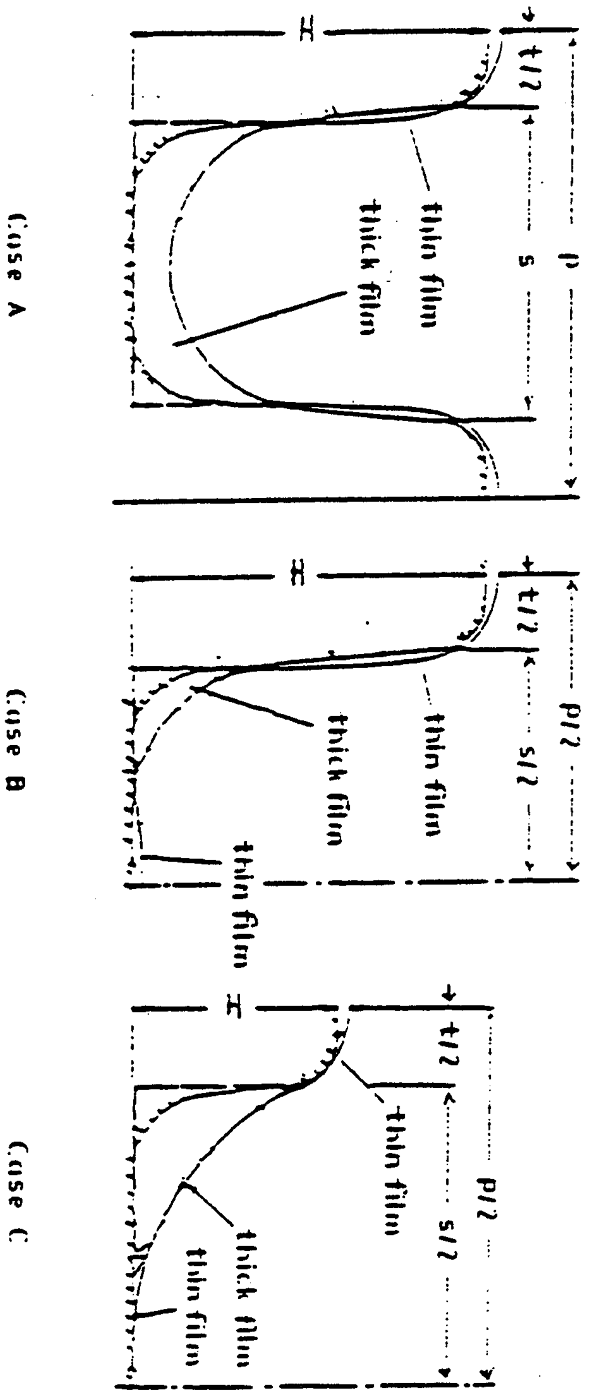

Figure 2.2. Three Subcases of the Honda Model. From Ref. [2].

with a low condensation rate where fin height is small relative to interfin spacing. Along the fin, surface heat transfer is determined from the flooding condition, case type, and by whether the condensate flow is gravity or surface tension dominated. In the interfin space, heat transfer is determined for the three cases for an unflooded condition only. No heat transfer is considered for the flooded interfin space. Expressions for the Nusselt number representing the flooded and unflooded regions are found and summed to yield an average Nusselt number. Honda's comparison of his model with available experimental data showed agreement to within 20 percent for 11 fluids and 22 finned tubes.

In 1992, Briggs, Wen, and Rose [Ref. 25] conducted a detailed review of the accuracy of various models to predict heat transfer for condensation on horizontal integral-finned tubes. The simple model of Beatty and Katz performed poorly because it did not account for surface tension effects. The Adamek and Webb model included an approximate surface tension effect and resulted in an improved enhancement prediction. The Honda model, which accounted for both the condensate flooding and the enhancing effect of surface tension drainage from the fins, was judged the most accurate for predicting heat transfer coefficients for steam condensation on horizontal integral finned tubes. Despite its accuracy, its complexity limits its use.

6. Adamek and Webb

In 1989, Adamek and Webb [Ref. 7] formulated a model that accounted for condensation on surfaces in the unflooded and flooded regions. It rivals Honda and Nozu in its complexity, yet is solvable without numerical methods. The model accounts for heat transfer on the fin tips, flanks, and interfin areas in the unflooded zone and on the fin tips in the flooded zone. It assumes no heat transfer in the other areas including the fin tips in the dropoff zone. Referring to Figure 2.3, the

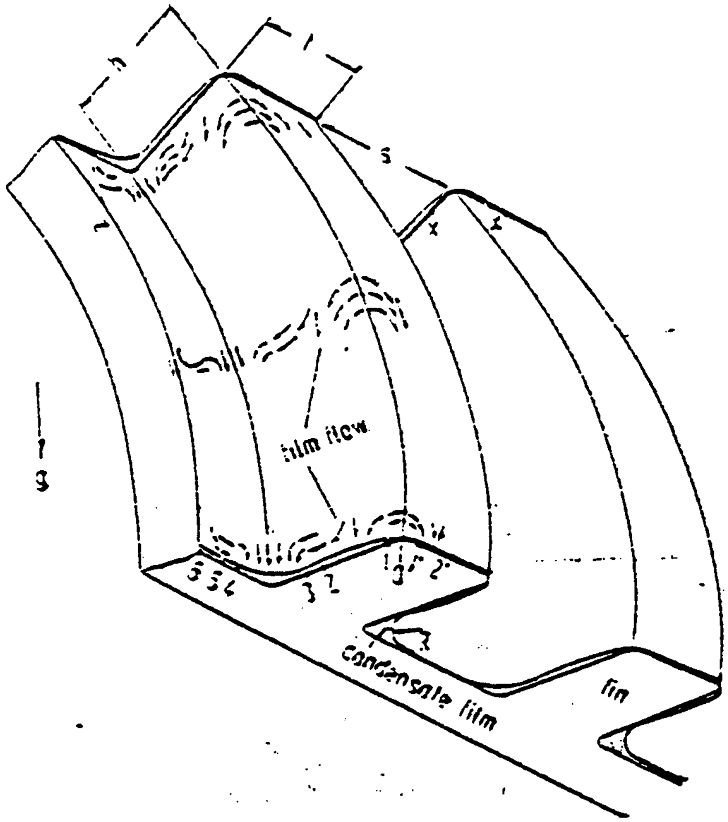

Figure 2.3. Illustration of the Condensate Flow Pattern Assumed by Adamek and Webb. From Ref. [7].

unit area of one fin pitch is divided into nine flow regions. Regions 0, 1′, and 2′ are labeled from the edge of the fin tip to its midpoint. Regions 1, 2, and 3 run down the fin flank to the root. Regions 4, 5, and 6 run from the fin root to the midpoint of the interfin area. If the condensation rates in the circumferential direction between each of the regions (m_{ij}) can be determined, their sum would be the total condensation rate ($\dot{M}$) for one-half the fin pitch. The heat transfer coefficient based on the area of one fin pitch is then calculated as

$$h_o = \frac{Q}{A_{eff}(T_{sat} - T_{wo})} \tag{2.27}$$

where the heat transfer rate (Q) is

$$Q = 2\dot{M}h_{fg}. \tag{2.28}$$

Calculation of the individual regional flows is achieved by determining whether they are gravity or surface tension controlled and then calculating the respective film thicknesses in each region and radius of curvature of the film at the fin root based on this dominant force.

This model was compared to the experimental results of 80 copper tubes of varying geometries and condensing fluids. The fluids included water, methanol, n-pentane, R-11, R-12, R-22, and R-113. Fin spacing, height, and thickness varied from 0.06 to 10 mm, 0.29 to 3.6 mm, and 0.06 to 1.0 mm respectively. The model predicted the heat transfer coefficient within 15 percent for 74 of the 80 tubes.

7. Rose

In 1987, Masuda and Rose [Ref. 16] developed a more complete accounting of the liquid retention on the fin flanks and interfin areas of the unflooded region. Figure 2.4 shows the profiles for static retention of liquid on a finned tube.

Column (b) refers to "long fin" geometries where fin height is relatively larger than the fin spacing. Column (c) refers to "short fin" geometries where fin height is relatively smaller than fin spacing.

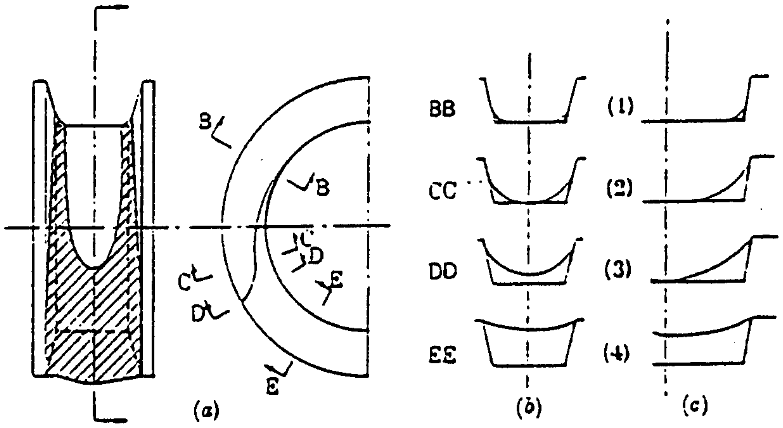

Figure 2.4. Configuration of Retained Condensate Along Tube Circumference for Briggs and Rose Model. From Ref. [16].

In the unflooded region for both geometries, the retained liquid forms a small "wedge" between the flanks of the fins and the tube surface in the interfin space (b1) and (c1). Moving circumferentially around the tube, four flooding conditions are considered, corresponding to the profiles in illustrations (b2), (b3), (c2), and (c3) respectively. Considering long fin tubes (column (b)), moving from the top of the tube to the flooded region, the size of the liquid wedges increases until they meet at the midpoint of the interfin space. This corresponds to $\phi = \phi_{f1}$, where the interfin space is just filled by liquid, but the fin flanks are not wholly wetted. Continuing downward, the meniscus rises until it reaches the fin tips. Here, $\phi = \phi_{f2}$, and the whole of the flank is just wetted and the liquid film at the center of the interfin space has finite thickness. Further movement around the tube will show an increase in the thickness of the liquid in the interfin space (b4).

For short fin tubes (column (c)), the wedges increase in size until they contact the fin tips. This corresponds to $\phi = \phi_{f3}$, where the fin flank is just completely wetted but the interfin space is not wholly wetted. Continuing along the tube, the wedges expand until they meet at the midpoint of the interfin space. At this point, $\phi = \phi_{f4}$, and the whole of the interfin space is just wetted and the contact angle of the liquid at the fin tip is nonzero. Further movement around the tube will show an increase in the thickness of the liquid in the interfin space (c4).

By considering the radius of curvature of the liquid profile, Masuda and Rose developed the following relations for flooding angle at each of the four positions

$$\cos\phi_{f1} = \frac{4\sigma_f}{\rho_f g s D_r} - \frac{D_f}{D_r}, \tag{2.29}$$

$$\cos\phi_{f2} = \frac{4\sigma_f}{\rho_f g s D_f} - 1, \tag{2.30}$$

$$\cos\phi_{f3} = \frac{2\sigma_f}{\rho_f g H D_r} - \frac{D_f}{D_r}, \tag{2.31}$$

and

$$\cos\phi_{f4} = \frac{16\sigma_f H}{\rho_f g (s^2 + 4H^2) D_f} - 1. \tag{2.32}$$

They recognized that heat transfer through the condensate film was minimal. Therefore, only heat transfer through the fin tips and through the thin film or "unblanked" areas of the fin flanks and interfin space in the unflooded region are considered. The following expression approximates the fraction of the fin flank "blanked" with a thick condensate film

$$f_f = \frac{\int_0^{\phi_f} r_c D_r \, d\phi}{\phi_f D_r H} \approx \frac{2\sigma_f}{\rho_f g D_r H} \frac{\tan(\phi_f/2)}{\phi_f}. \tag{2.33}$$

Similarly, the fraction of the interfin space blanked is

$$f_s = \frac{2\int_0^{\phi_f} r_c D_r d\phi}{\phi_f D_r s} \approx \frac{4\sigma_f}{\rho_f g D_r s}\,\frac{\tan(\phi_f/2)}{\phi_f}\,. \qquad \textbf{(2.34)}$$

These equations for blanking are only valid for long rectangular section fins where ($D_r/D_f \approx 1$) and $H > s/2$. For these fins, $\phi_{f1} \approx \phi_{f2}$ and so the flooding angle (ϕ_f) is set equal to ϕ_{f2} which is the same as the Rudy and Webb equation (2.6).

For rectangular fins the "active" area enhancement (ξ), defined as the combined areas of the fin tips and unblanked portions of the flank and interfin space in the unflooded region divided by the smooth tube area of $D_o = D_r$, is

$$\xi = \frac{D_r s \phi_f (1-f_t) + \frac{D_f^2 - D_r^2}{2}\phi_f (1-f_f) + \pi D_f t}{\pi D_r (s+t)}\,. \qquad \textbf{(2.35)}$$

Actual experimental heat transfer enhancements are much greater than ξ because the fin flanks behave as small vertical surfaces with significantly higher heat transfer coefficients than a horizontal smooth tube. Therefore, the second term in the above expression needs to be multiplied by a weighting coefficient (κ_1), where

$$\kappa_1 = \left(\frac{0.943}{0.728}\right)\left(\frac{D_r}{H_v}\right)^{1/4} \qquad \textbf{(2.36)}$$

and the mean vertical fin height (H_v) is approximated by

$$\begin{aligned} H_v &= \frac{\phi_f H}{2-\sin\phi_f} && \frac{\pi}{2} < \phi_f \le \pi \\ H_v &= \frac{\phi_f H}{\sin\phi_f} && \phi_f \le \frac{\pi}{2}\,. \end{aligned} \qquad \textbf{(2.37)}$$

In addition, surface tension thins the condensate film at locations where the liquid radius of curvature varies relatively rapidly. This occurs on the fin tip, flank, and interfin space. Therefore the entire numerator of equation (2.35) needs to be multiplied by a second weighting factor (κ_2) where κ_2 would be proportional to surface tension. The weighted "active" area enhancement (ξ_W) is thus

$$\xi_W = \frac{\kappa_2\left[D_r s\phi_f(1-f_t) + \kappa_1\left(\frac{D_f^2 - D_r^2}{2}\right)\phi_f(1-f_f) + \pi D_f t\right]}{\pi D_r(s+t)} . \qquad \textbf{(2.38)}$$

With κ_1 = 2.2 and κ_2 = to 1.5, fair prediction of enhancement was found for steam condensation on copper integral fin tubes of 1.59 mm fin height, 0.5 mm fin thickness, and interfin spacing of 0.5 to 4.0 mm.

In later work, Rose [Refs. 26, 27] defined the heat transfer enhancement as the ratio of heat transfer coefficients of a finned tube based on a smooth tube area of fin root diameter (D_r) to that of a smooth tube of outside diameter (D_o) equal to the finned tube root diameter. Both heat transfer coefficients are evaluated at the same vapor side temperature difference.

In later work, Rose [Refs. 26, 27] defined the heat transfer enhancement as the ratio of heat transfer coefficients of a finned tube based on a smooth tube area of fin root diameter (D_r) to that of a smooth tube of outside diameter (D_o) equal to the finned tube root diameter. Both heat transfer coefficients are evaluated at the same vapor side temperature difference.

Equation (2.38) was modified by including the heat fluxes in each area component. Each heat flux consisted of a gravity and surface tension term. The constants κ_1 and κ_2 were replaced with the constants B_1, B_{tip}, B_{flank}, and B_{int} . Briggs and Rose [Ref. 28], later incorporated fin efficiency into the model. The final form of the equation for enhancement is

$$\epsilon_{\Delta T} = \frac{Q_{flood} + Q_{fin} + Q_{int}}{Q_{smooth}}. \tag{2.39}$$

where the heat transfer rates from the flooded tips, unflooded fin and interfin space, and smooth tube are

$$Q_{flood} = (\pi - \phi_f) D_f t q_{tip,flood}, \tag{2.40}$$

$$Q_{fin} = \phi_f \left[D_f t q_{tip} + (1 - f_f) \frac{D_f^2 - D_r^2}{2} q_{flank} \right], \tag{2.41}$$

$$Q_{int} = \phi_f (1 - f_s) D_r s q_{int}, \tag{2.42}$$

and

$$Q_{smooth} = \pi D_o (s + t) q_{smooth}. \tag{2.43}$$

The respective heat fluxes are

$$q_{tip,flood} = \frac{k_m (T_{tip,flood} - T_b)}{H}, \tag{2.44}$$

$$q_{tip} = \left[\frac{\rho_f k_f^3 h_{fg} \Delta T_{tip}^3}{\mu_f} \left(0.281 \frac{\rho_f g}{D_f} + \mathbf{B}_{tip} \frac{\sigma_f}{t^3} \right) \right]^{1/4}, \tag{2.45}$$

$$q_{flank} = \left[\frac{\rho_f k_f^3 h_{fg} \Delta T_{flank}^3}{\mu_f} \left(0.791 \frac{\rho_f g}{H_v} + \mathbf{B}_{flank} \frac{\sigma_f}{H^3} \right) \right]^{1/4}, \tag{2.46}$$

$$q_{int} = \mathbf{B}_1 \left\{ \frac{\rho_f k_f^3 h_{fg} \Delta T_{int}^3}{\mu_f} \left[(\zeta(\phi_f))^3 \frac{\rho_f g}{D_r} + \mathbf{B}_{int} \frac{\sigma_f}{s^3} \right] \right\}^{1/4}, \tag{2.47}$$

and

$$q_{smooth} = 0.728\left(\frac{\rho_f^2 g k_f^3 h_{fg} \Delta T^3}{\mu D_r}\right)^{1/4} . \qquad \textbf{(2.48)}$$

The expression $\zeta(\phi_f)$ is needed to determine the mean condensate film thickness in the thin film interfin space and can be approximated by

$$\zeta(\phi_f) \approx 0.874 + 0.001991\,\phi_f - 0.02642\,\phi_f^2 + 0.00553\phi_f^3 - 0.001363\phi_f^4 . \qquad \textbf{(2.49)}$$

The constants B_1, B_{int}, B_{tip}, and B_{flank} were empirically determined by curve fitting condensation data on copper tubes from seven investigations, four different fluids, and fourty-one different fin geometries. The best fit was found by setting B_1 equal to 2.96 and the other B values set equal to 0.143. The Briggs and Rose model gave a predictive accuracy of 15 to 25 percent when compared with experimental data.

F. RESEARCH ON FILM CONDENSATION ON INTEGRAL FINNED TUBES AT THE NAVAL POSTGRADUATE SCHOOL

Condensation on finned tubes has been studied at NPS since 1984. The majority of the experimentation has been done with copper tubes. Flook [Ref. 29] in 1985 and Mitrou [Ref. 30] in 1986 tested tubes of varying thermal conductivities. They showed that materials with high thermal conductivity exhibited greater enhancement than lower conductivity tubes. In 1993, Cobb [Ref. 6] studied the effects of varying thermal conductivity on steam condensation. He tested finned tubes of constant fin spacing and thickness manufactured from copper, aluminum, 90-10 copper-nickel, and stainless steel. He noted that tube conductivity had a significant effect on enhancement with the lowest conductivity tube (stainless steel) at larger fin heights yielding heat transfer coefficients less than a smooth tube. He also compared his experimentally determined heat transfer coefficients with the Beatty and Katz [Ref. 17] and Rose [Ref. 26] models. He found that both theoretical models underpredicted enhancement for copper tubes under high heat flux conditions. For the other materials, as thermal conductivity decreased, Beatty and Katz overpredicted the results with increasing error while the Rose model closely predicted the results.

Meyer [Ref. 2] continued the work of Cobb by comparing the experimentally determined heat transfer coefficients for steam condensation on tubes made of the four materials to the predictive models of Beatty and Katz [Ref. 17], Briggs and Rose [Ref. 28], Adamek and Webb [Ref. 7], and Honda [Ref. 15]. He judged the Rose model best, yet found that it consistently underpredicted the experimental results. The Beatty and Katz model consistently overpredicted experimental results especially for the lower temperature vacuum runs where surface tension was greater. The Adamek and Webb model followed the experimental trend, but overestimated the results. The Honda model performed erratically. Meyer noted that increasing fin height improved enhancement for all tube materials except stainless steel. The lower conductivity stainless steel tubes showed a decreasing trend in enhancement as fin height was increased from 0.5 mm to 1.5 mm. He attributed this to increased flooding of the tube and lower fin efficiency.

III. SYSTEM OVERVIEW

A. EXPERIMENTAL APPARATUS

The apparatus used for this research was originally constructed by Krohn in 1982 [Ref. 31]. Major modification to the condenser section was done by Swenson in 1991 [Ref. 32]. Since then, the apparatus was used successfully by O'Keefe [Ref. 33], Long [Ref. 34], Cobb [Ref. 6], and Meyer [Ref. 2] to test condensation on single horizontal tubes of various configurations. Fig 3.1 contains a general schematic of the overall system.

Steam is generated in a Corning Pyrex glass cylindrical boiler of 0.3048 m diameter and 0.5 m height with a maximum working pressure of 72.6 kPa (10.5 psig). It contains ten vertically mounted 4 kW, 440 VAC Watlow stainless-steel immersion heaters connected in parallel. The heaters have a total resistance of 5.76 ohms throughout their range of operation. The boiler is mounted on a metal stand with four adjustable legs so that the system can be plumbed. The boiler is filled with water by gravity drain or vacuum drag from a distilled water tank through a fill/drain valve. Distilled water for the apparatus is made from tap water by a Barnstead Fi-streem 4 ltr/hr glass still.

Steam from the boiler passes up through a cylindrical section of Pyrex glass with an inside diameter of 0.15 m and a length of 2.13 m. Two 90° Pyrex glass elbows redirect the steam back down a second similar cylindrical section of 1.52 m in length. All glass piping have a maximum working pressure of 103 kPa (15 psig). The piping is covered with Halstead insulating foam to minimize premature condensation.

Steam then enters a stainless steel test section containing the horizontally mounted condenser tube. The test section is fitted with openings for Teflon and Nylon inserts that support the horizontal tube and provide a coolant flow

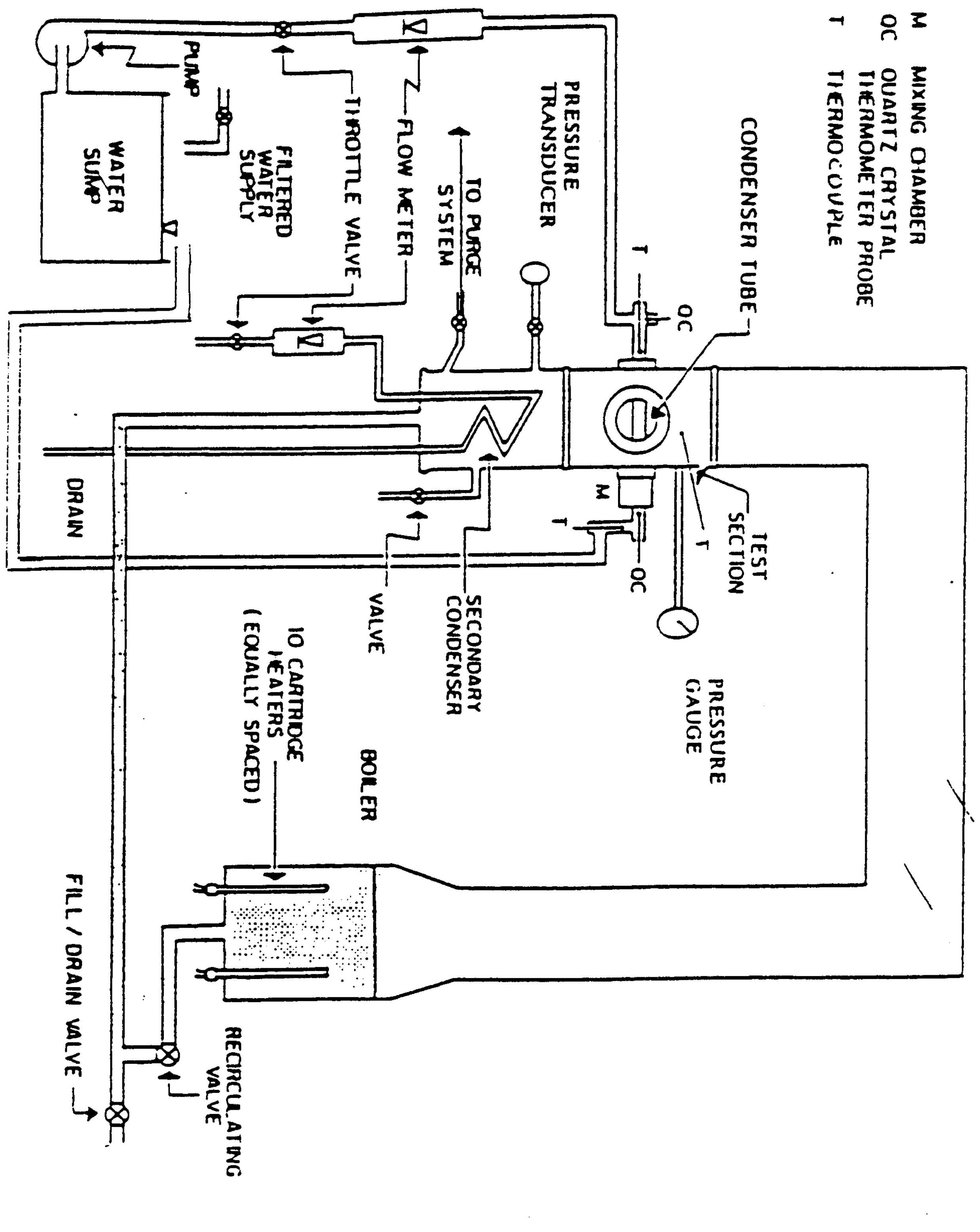

Figure 3.1. Schematic of the Single Tube Test Apparatus. After Ref. [34].

path. These inserts contain O-rings to seal the condenser from the ambient atmosphere and the coolant. The test section also contains a circular hole that accomodates a viewing port so that the condensation process can be observed. A smaller port in the test section allows connection of a pressure gage and thermocouple well.

Steam not condensed in the test section passes into a final Pyrex glass cylinder containing an auxiliary condenser. The auxiliary condenser is constructed of a single copper coil mounted to a stainless steel base. It was installed in 1991 and replaced the previous double coil condenser. The auxiliary condenser section collects all the condensate and returns it to the boiler through a gravity drain in the baseplate. Two stainless steel side plates are mounted to the glass cylinder with penetrations for a pressure bleed valve, a vacuum line, and a pressure transducer. The auxiliary condenser cooling water is supplied directly from the building water main and passes through a pressure regulator that eliminates most pressure fluctuations. Saturation temperature in the apparatus is controlled by adjusting a throttle valve in the auxiliary condenser coolant flow line. Water exiting the condenser is discharged to the building drain.

Cooling water for the test section originates in a stainless steel sump tank. Tap water flows into the sump and an overflow maintains a constant water height. Two centrifugal pumps connected in series draw suction from the sump. A throttling valve and calibrated rotameter on the discharge side of the pumps allow control of the cooling water flow. After flowing through the test tube, cooling water flows into a nylon mixing chamber so that the average coolant temperature can be accurately measured. In the mixing chamber, water is channeled through a center hole, then flows radially outward and through a set of four holes, and then flows inward and exits through another center hole. Coolant then returns to the sump where it mixes with the incoming cold tap water before recyling to the test section. Thermocouple wells and quartz thermometer probe connections are installed on the coolant lines prior to the test section and following the mixing chamber. Details of the test section are shown in Figure 3.2.

Noncondensible gases are removed through a vacuum system shown in Figure 3.3. Vapors are removed at a suction port at the base of the auxiliary condenser section. The vapors then pass through an internal condensing coil located in the cooling sump where any steam is condensed and collected in a plexiglass vacuum chamber. The noncondensibles are passed through a vacuum pump and expelled to the atmosphere. The Gast model 2567-V108 vacuum pump was installed in 1991 and replaced a compressed air actuated air ejector. The pump can draw a vacuum of 130 mm Hg. A check valve is installed to prevent back flow when the pump is stopped. An IMC Magnetics model 12 electric fan cools the vacuum pump.

Cast iron flanges with Buna-N rubber gaskets join the boiler, glass piping, and condenser sections and are secured with fasteners tightened in a star pattern to 60 in-lbs maximum torque. The apparatus was leak tested by placing it under an initial vacuum of 4.96 kPa absolute (0.72 psia). After 18 days, the system pressure was 12.81 kPa (1.86 psia) giving a mean leak rate of 0.434 kPa (0.063 psi) per day.

B. SYSTEM POWER AND INSTRUMENTATION

Power for the boiler heaters is controlled by a Halmar system located in the laboratory switchboard. A schematic of the system is shown in Figure 3.4. Four-hundred-forty VAC line voltage is reduced by a factor of 100 in a differential input precision voltage attenuator. The stepped-down voltage is then passed through a True-Root-Mean-Square (TRMS) converter in which the integration period is reduced to about

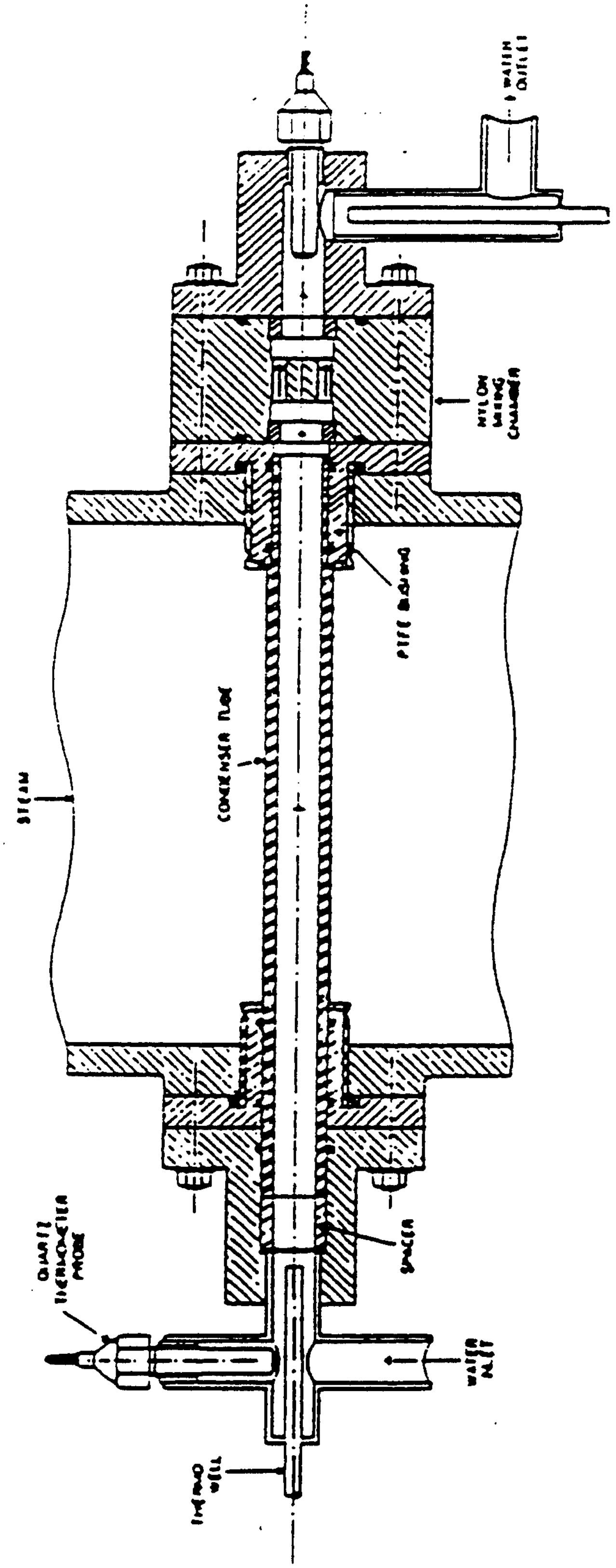

Figure 3.2. Schematic of the Test Section. After Ref. [34].

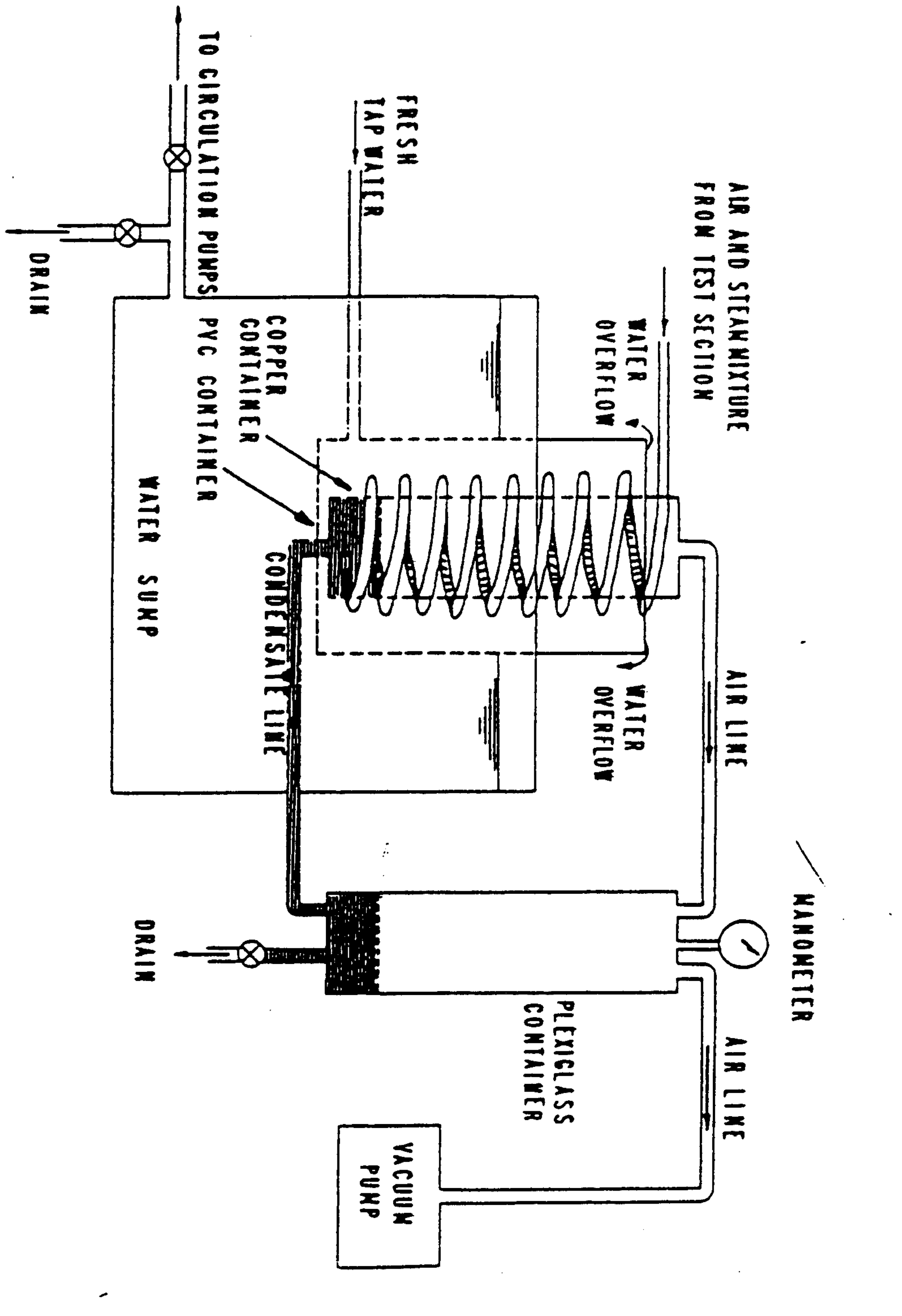

Figure 3.3. Schematic of the Purging System. From Ref. [34].

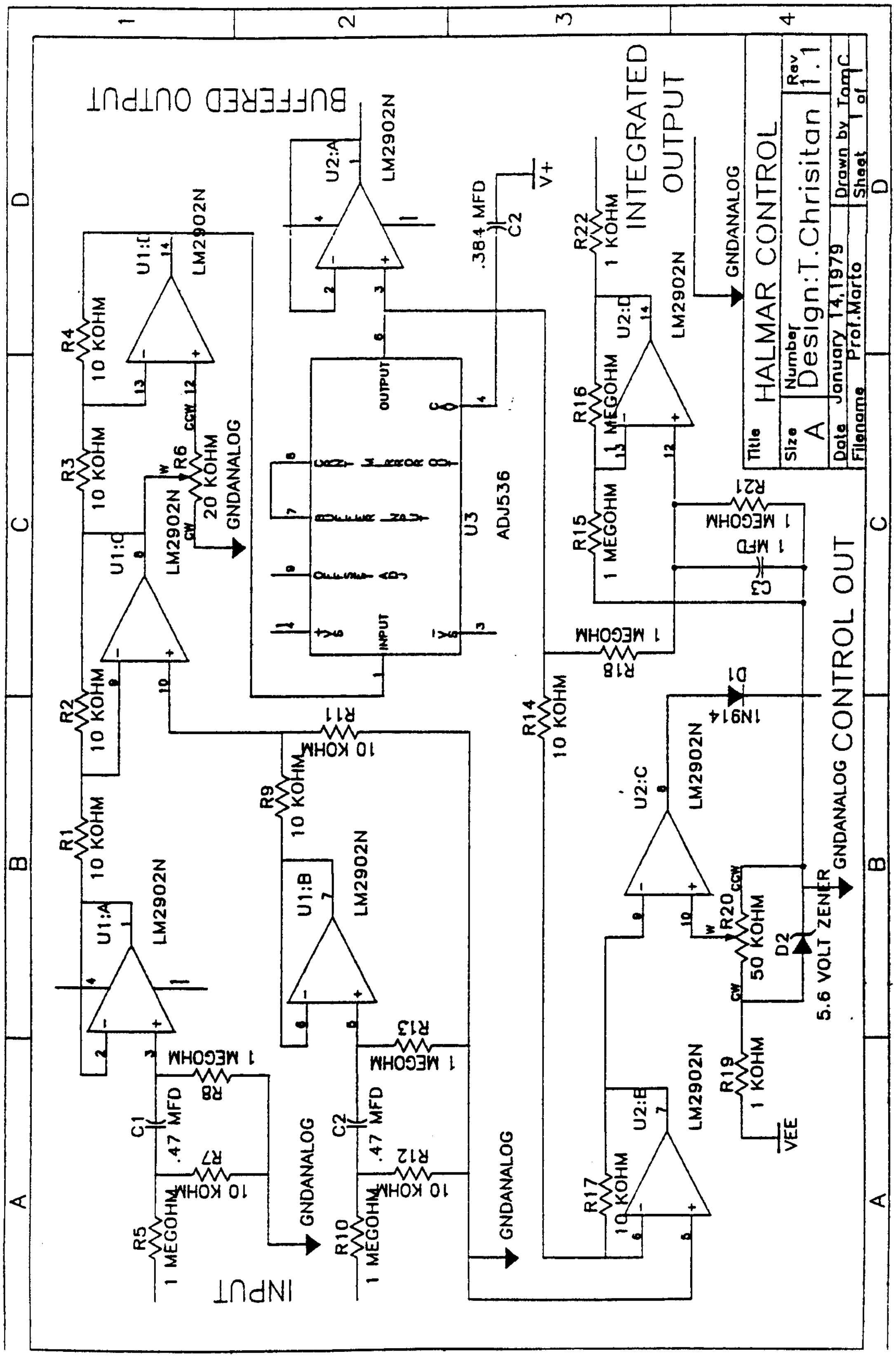

Figure 3.4. Schematic of Halmar Power Control System. From Ref. [35].

100 ms. The output of the TRMS converter is then buffered and compared to a reference voltage from a panel-mounted potentiometer. The comparator output is fed to the control input of a Halmar silicon-controlled rectifier power supply that applies the actual voltage to the heaters. The TRMS converter output is also paralleled through a filter and then inputted to the data acquisition system for voltage and current measurement [Ref. 35]. An AC voltmeter and ammeter are mounted on the switchboard for visual reference only.

Saturated steam temperature in the test condenser is measured by two type-T copper/constantan thermocouples positioned in a well whose tip is located in the steam flow between the test tube and condenser shell. Ambient temperature is measured with a type-T copper/constantan thermocouple located in the proximity of the apparatus. The inlet and outlet test tube coolant temperatures are measured with an HP-2804A quartz crystal thermometer. Two copper/constantan thermocouples fitted into wells also provide a crude check of the quartz thermometer measurements.

Test condenser pressure is monitored by both a Heise 0-103 kPa (0-15 psia) pressure gage and a Setra model 204 pressure transducer. These were installed in 1992 and replaced a mercury manometer that was attached to the apparatus. Both devices measure gage pressure relative to atmospheric and require a local atmospheric pressure value to convert from gage to absolute pressure [Ref. 36]. It was discovered that the pressure transducer had previously been operated incorrectly. Meyer and previous researchers compared the transducer pressure to a constant 14.78 psi atmospheric pressure in all experimental trials. Because they calculated the mass fraction of noncondensibles gases in the apparatus from the pressure transducer, this constant value of atmospheric pressure would have given them false and inconsistent noncondensible fractions for different experiments. Its effect on their judgement of experimental validity is unknown. Measurements of experimental pressure for this thesis were determined by the transducer output relative to atmospheric pressure measured from a mercury barometer located in the adjacent calibration laboratory.

Coolant flow is measured by a Fischer and Porter model FP-1-35-G-10/83 rotameter installed on the discharge side of the coolant pumps. Complete operating instructions for the experimental apparatus are contained in Appendix A.

Because the last instrument calibration was reported by Swenson in 1992 [Ref. 32], all thermocouples, the quartz thermometer, the rotameter, and the Halmar power supply voltage output were recalibrated. The calibration procedure and voltage correlations are discussed in Appendix B. The pressure transducer and Heise gage were not calibrated due to lack of campus facilities. A comparison of the last and current calibration correlations showed agreement within 0.25°C for the thermocouples, 0.025°C for the quartz thermometers, and 1 percent for the rotameter in the experimental ranges. These close comparisons indicate that the lack of recent instrument calibration for Meyer's experiments should not have affected his results.

C. DATA ACQUISITION

An HP-3497A data acquisition system and the quartz thermometer unit are linked to a HP-9826 computer and Think-Jet printer. HP-BASIC program DRPALL contained in Appendix C is used to read, store, and process the experimental data. The data acquisition subroutine prompts for the tube and fin dimensions, tube material, and pressure condition for each experimental trial. For each data point, coolant flow from the rotameter and the gage pressure are manually entered. The data acquisition system remotely reads the system voltage, the pressure transducer voltage, the coolant inlet and outlet temperatures from the quartz thermometers, and the coolant, steam, and ambient thermocouple voltages. Five readings of the transducer, quartz thermometers, and thermocouples are taken over approximately fourty-five seconds and then averaged to minimize the error due to system fluctuations.

For each data point, the steam temperature, coolant temperature rise, system voltage, and noncondensible gas mass fraction are reported for visual inspection. When these values lie within the proper range and the coolant temperature rise for two consecutive data readings lies within 0.01°C at the same flow rate, the most recent pressure, voltage, flow, and steam, ambient, and coolant temperatures are stored in a file for future analysis. A complete experimental trial consists of 14 data points. Data points are taken at ten percent rotameter increments from 80 to 20 percent flow. To assure their validity, data points are then taken in reverse order from 20 to 80 percent flow.

D. CONDENSER TUBES

1. Description

The apparatus is designed for condenser tubes 228.6 mm (9 in) long. The inlet and outlet shoulders that fit within the inserts are 60.325 mm (2-3/8 in) and 34.925 mm (1-3/8 in) long respectively, leaving an active condensation length of 133.35 mm (5-1/4 in). The tube O.D. at the ends is machined to a standard pipe size of 15.88 mm (5/8 in). Tube inside and root diameters vary dependent on the source of supply and fabricator. Fin spacing of 1.5 mm and fin thickness of 1.0 mm were selected as these were previously determined to be optimum values for steam condensation enhancement on copper tubes [Refs. 8, 9, and 37].

Discrepencies were found in the reported dimensions of the tubes tested by Meyer. Multiple measurements of fin dimensions, root diameter, and inside diameter were taken with a digital caliper. Significant taper from one end of the tube to the other was noted of up to 0.07 mm in fin height, up to 0.21 mm in root diameter, and up to 0.20 mm in inside diameter. The degree of taper was linear along the tube length and was probably due to the machining process. If the average dimensions were used in experimental data reduction, it is unlikely that this taper would have significantly affected the results. However, a comparison of these averaged measured values and the dimensional values reported by Meyer show disagreement of up to 0.15 mm in fin height, up to 0.15 mm in root diameter, and up to 0.32 mm in inside diameter. The inside and root diameters are used in calculating the heat transfer coefficients and enhancement. These differences could have affected his results. Table 3.1 shows the correct dimensions of Meyer's tubes.

Fabrication of the new set of stainless steel tubes was accomplished by the NPS machine shop on a numerical lathe with a common ASTM 304 stainless steel tube stock. This assured dimensional consistency and taper of less then 0.04 mm for fin dimensions and less than 0.12 mm for diameters in each tube. Comparisons among tubes showed a range of less than 0.01 mm in fin width and spacing, less than 0.13 mm in inside diameter, and less than 0.19 mm in root diameter. Therefore, the only significant dimensional variable among tubes was fin height. The fin geometries, diameters, and materials of the new tubes tested are summarized in Table 3.2.

2. Surface Treatment of Condenser Tubes

To ensure complete film condensation on the test tubes, special surface treatment was performed before testing. Swenson [Ref. 32] and O'Keefe [Ref. 33] both noted that dropwise condensation was difficult to prevent, particularly on copper tubes. A caustic soda treatment originally proposed by Georgiadis [Ref. 38] was used by Meyer [Ref. 2] to oxidize the tube surface and gain filmwise condensation on his copper,

Type	Fin Width (mm)	Fin Spacing (mm)	Fin Height (mm)	I.D. (mm)	Root Diameter (mm)	Material
Finned	1.0	1.5	0.42	12.65	13.77	STS
Finned	1.0	1.5	0.60	12.69	13.80	STS
Finned	1.0	1.5	1.02	12.69	13.84	STS
Finned	1.0	1.5	1.11	13.02	14.02	STS
Finned	1.0	1.5	1.46	12.93	14.03	STS

Table 3.1. Actual Dimensions of Meyer's [Ref. 2] Stainless Steel Tubes

Type	Fin Width (mm)	Fin Spacing (mm)	Fin Height (mm)	I.D. (mm)	Root Diameter (mm)	Material
Smooth	--	--	--	13.21	14.10	304 STS
Finned	1.0	1.5	0.16	13.20	14.25	304 STS
Finned	1.0	1.5	0.28	13.15	14.23	304 STS
Finned	1.0	1.5	0.38	13.08	14.29	304 STS
Finned	1.0	1.5	0.48	13.11	14.26	304 STS
Finned	1.0	1.5	0.75	13.10	14.25	304 STS
Finned	1.0	1.5	0.95	13.08	14.24	304 STS
Finned	1.0	1.5	1.26	13.08	14.21	304 STS
Finned	1.0	1.5	1.42	13.10	14.28	304 STS

Table 3.2. New Stainless Steel Tubes Tested

copper-nickel, aluminum, and stainless steel tubes. The procedure is:

1. Thoroughly scrub new tubes inside and out with a soft bristle brush using water and a mild detergent to remove dirt and oil.
2. Soak tubes for one hour in acetone to remove remaining oil. Thoroughly rinse with distilled water.
3. Wearing protective goggles and gloves, mix a solution of equal parts by volume of ethyl alcohol and sodium hydroxide (caustic soda). Do not use any previously mixed solution because the caustic soda absorbs carbon dioxide from the air limiting its effectiveness. Heat the solution in a hot water bath until it achieves the consistency of thin paste. Thin with added alcohol if necessary.
4. Place the cleaned tube in a steam bath. Apply the caustic soda solution with a brush over the active area of the tube. Rotate the tube while applying to ensure the entire tube surface is treated. Apply the solution at ten minute intervals for one hour. Note: For aluminum tubes only, discontinue solution treatment once a continuous oxide layer forms on the tube surface. Additional treatment could reduce the tube dimensions from excess corrosion.
5. At the end of the treatment procedure, rinse the tube with acetone and then distilled water. Examine the surface film for continuity. If an unbroken film does not exist, repeat Step 4. Do not touch the active area of the tube once the desired film condition is achieved.

Although Georgiadis cited no reference for this procedure, a similar treatment was found for preparing stainless steel for electroplating [Ref. 39]. The metal is soaked in a five percent by weight solution of caustic soda while a seven to twelve volt potential is applied between the solution and metal. The process is discontinued once water forms an unbroken film on the metal.

During retesting of Meyer's stainless steel tubes, Georgiadis' tube treatment procedure proved inadequate. Despite repeated caustic soda treatment of the tubes, dropwise condensation could not be prevented. Direct immersion of the tubes in a ten percent (by volume) solution of caustic soda at 80°C was also ineffective. Several copper and copper-nickel tubes were also treated and retested with the same poor results. After several months of repeated dropwise trials, an acid treatment procedure was tried as an alternative [Ref. 40]. Stainless steel tubes were soaked in a solution of 225 ml nitric acid (70% molar), 75 ml hydrochloric acid (37% molar), and 1,200 ml distilled water at 58°C for 15 minutes. Afterwards, they were soaked for 15 minutes in a solution of 225 ml nitric acid and 1,275 ml water at 65°C. When this procedure was used on Meyer's stainless steel tubes that had been previously treated with caustic soda, a white marbled finish formed on the tubes. No measurable change in tube dimensions was observed. This finish proved effective at maintaining film condensation during retest of Meyer's stainless steel tubes. No retest of Meyer's copper or copper-nickel tubes was possible. The acid treatments referenced for treatment of these metals [Ref. 40] severely damaged the tubes, decreasing the fin and tube dimensions, rounding the rectangular fin profiles, and in some cases, completely eroding the interfin space.

When the acid treatment was used on the new set of stainless steel tubes that had no prior caustic soda treatment, no white finish formed and film condensation could not be maintained during experimentation. Therefore, the combination Georgiadis' caustic treatment followed by the acid treatment was used. This combination was used successfully for testing most of the new stainless steel tubes although repeated treatments were often necessary. The combination solution treatment was ineffective for testing the smooth and 0.16 mm fin height tubes.

For these two tubes, another approach was sought to oxidize the surface. The tubes were heated with an oxyacetylene torch and then air cooled to obtain a brown oxide layer on the tube surface. This proved an effective and much simpler method for promoting film condensation. No measurable change in tube or fin dimensions was noted after heat treatment. Therefore, the layer must be extremely thin and should not affect the tube thermal conductivity [Ref. 41]. Two of the tubes that were tested successfully after the combination solution treatment were subsequently heat treated and retested. These tests yielded similar experimental results demonstrating that the brown oxide layer formed from heat treatment did not significantly effect the thermal characteristics of the tube.

3. Use of Tube Inserts

Previous NPS researchers used twisted tape, wire-wrap, and the Cal Gavin HEATEX inserts within tubes. These inserts significantly increase the overall heat transfer rates at the expense of an increase in the pressure drop through the tube. Inserts are used in experimental applications to realize a larger temperature rise in the coolant flow and decrease the uncertainty of heat transfer calculations. Early investigations had shown that without the use of inserts, the coolant side thermal resistance could be as much as 50 to 60 percent of the overall thermal resistance [Ref. 37]. A small discrepancy in the coolant side thermal resistance could therefore translate into a substantially larger discrepancy in the overall heat-transfer coefficient. An insert enhances the coolant side heat transfer coefficient thereby improving the accuracy of the experimentally determined overall heat transfer coefficient. It also reduces circumferential wall temperature variation and thermal entrance effects by inducing quicker turbulent boundary-layer growth.

The favored insert for the most recent NPS investigations was the HEATEX insert. It is a wire mesh insert that disturbs the laminar boundary layer at the tube wall [Ref. 42].

O'Keefe [Ref. 33] found that the HEATEX insert gave a twenty percent increase in the overall heat transfer coefficient compared to the data from tubes without an insert. Swenson [Ref. 32] compared the inside heat transfer coefficients for HEATEX and wire wrap inserts to data runs with no insert. He reported that the inside heat transfer coefficient doubled when an insert was used in place of a smooth tube.

E. MODIFICATIONS TO APPARATUS

Minor changes were made to the experimental apparatus. The sight glass on the test condenser was modified. A Phenolic spacer and a plastic outer pane were attached over the inner glass pane. Holes were drilled into the side of the Phenolic spacer so that air from a heat gun could be blown to defog the inner glass. The gate-type throttle valve between the cooling water pumps and rotameter was replaced with a globe valve. This allowed more steady control of cooling water flow to the test tube. The auxiliary condenser regulator outlet valve position was also reversed so that the arrow on the valve body coincided with the direction of coolant flow.

It was observed that the Teflon spacer that supported the inlet end of the test tube did not protrude completely to the beginning of the finned area. Approximately 4 mm of the smooth tube shoulder was exposed. Experiments conducted with this condition would overstate the experimentally determined outside heat transfer coefficient because additional outside area was exposed to condensation. This original spacer was used for retesting Meyer's tubes so that the experimental conditions would be duplicated. A correctly sized spacer was installed for testing the new set of tubes.

IV. DETERMINATION OF HEAT TRANSFER COEFFICIENTS

A. DATA REDUCTION

The total heat transfer rate (Q) across the test tube is calculated directly from the coolant mass flow rate ($\dot{m}$) and the coolant temperature rise through the tube as

$$Q = \dot{m} C_p (T_{out} - T_{in}) \qquad \textbf{(4.1)}$$

where T_{in} and T_{out} are the coolant inlet and outlet temperatures and C_p is the specific heat. The total heat transfer rate can also be expressed in terms of the overall heat transfer coefficient (U_o), the effective outside condensing area (A_o), and the log-mean-temperature-difference ($LMTD$) as

$$Q = U_o A_o (LMTD) \qquad \textbf{(4.2)}$$

where

$$LMTD = \frac{T_{out} - T_{in}}{\ln\left(\dfrac{T_{sat} - T_{in}}{T_{sat} - T_{out}}\right)} . \qquad \textbf{(4.3)}$$

Substituting equation (4.1) into equation (4.2) yields an expression for direct calculation of U_o from the experimentally obtained heat flux (q'') and $LMTD$,

$$U_o = \frac{\dot{m} C_p (T_{out} - T_{in})}{A_o (LMTD)} = \frac{q''}{LMTD} . \qquad \textbf{(4.4)}$$

The overall heat transfer coefficient is related to the overall thermal resistance from steam to the coolant by

$$R_{total} = R_i + R_w + R_o = \frac{1}{U_o A_o} \qquad \textbf{(4.5)}$$

where the inside coolant, outside vapor, and wall resistances are given respectively by

$$R_i = \frac{1}{h_i A_i} \tag{4.6}$$

$$R_o = \frac{1}{h_o A_o} \tag{4.7}$$

and

$$R_w = \frac{\ln(D_r/D_i)}{2\pi L k_m}. \tag{4.8}$$

Substituting equations (4.6) and (4.7) into equation (4.5) gives

$$\frac{1}{U_o A_o} = \frac{1}{h_i A_i} + R_w + \frac{1}{h_o A_o}. \tag{4.9}$$

The effective outside condensing area of the tube (A_o) is calculated as

$$A_o = \pi D_r L. \tag{4.10}$$

For computing the inside effective area, two different conditions need to be considered. Over the inside heat transfer surface, radial heat transfer from steam to coolant takes place over the "active" tube length (L) where steam condenses on the outer surface. Beyond the "active" length on either side, the tube ends are insulated on their exterior by the Teflon inserts. Nevertheless, axial heat transfer takes place along the inlet (L_1) and outlet (L_2) lengths. To account for this axial "fin" effect, an extended longitudinal fin approximation and associated fin efficiencies are used to compute the inside area as

$$A_i = \pi D_i (L + L_1\eta_1 + L_2\eta_2). \tag{4.11}$$

The fin efficiencies (η_1 and η_2) for the inlet and outlet lengths are given by

$$\eta_1 = \frac{\tanh(M_1 L_1)}{M_1 L_1} \tag{4.12}$$

and

$$\eta_2 = \frac{\tanh(M_2 L_2)}{M_2 L_2}, \tag{4.13}$$

where

$$M_1 = \sqrt{\frac{h_i P_1}{k_m A_1}} \tag{4.14}$$

and

$$M_2 = \sqrt{\frac{h_i P_2}{k_m A_2}}. \tag{4.15}$$

The fin perimeters (P_1 and P_2) and the cross-sectional areas (A_1 and A_2) for tube ends of equal diameters are given by

$$P_1 = P_2 = \pi D_i \tag{4.16}$$

and

$$A_1 = A_2 = \frac{\pi}{4}(D_o^2 - D_i^2). \tag{4.17}$$

With A_o, A_i, R_w, and U_o all known, the only unknown quantities in equation (4.9) are the outside (h_o) and inside (h_i) heat transfer coefficients.

The most accurate way to obtain inside and outside heat transfer coefficients is to directly measure the vapor temperature, mean inside and outside wall temperatures, and the coolant temperature. However, the measurement of tube wall temperatures requires the use of an instrumented tube with thermocouples embedded in the wall. The fabrication of such tubes is expensive and time consuming. It is especially impractical if a large number of tubes are to be tested. Moreover, the extremely delicate thermocouples are easily damaged. The modified Wilson plot technique provides a simpler alternative to solve for both the outside and inside heat transfer coefficients simultaneously.

B. MODIFIED WILSON PLOT TECHNIQUE

In 1915, Wilson [Ref. 43] developed a method for indirectly determining the inside and outside thermal resistance from an overall resistance. Wilson's original method required a constant heat flux to the system in order to obtain h_i and h_o. Since the cooling water velocity is varied during the experiments in this study, it is difficult to maintain a constant heat flux without varying boiler power and steam velocity. Briggs and Young [Ref. 44] proposed a modified Wilson technique to accomodate varying flow rates and temperatures. Their modification also provided separate techniques for boiling, condensation, and no-phase-change conditions.

The method, however, still requires that h_i and h_o be expressed in terms of the physical, flow, and thermal properties of the coolant and condensate. The inside and outside heat transfer coefficients can be expressed as the product of a leading coefficient (C_i and C_o) and a parameter (Ω and Z) which is a function of the thermophysical properties and flow variables, as discussed in the next two sections, to get

$$h_i = C_i\Omega \qquad \textbf{(4.18)}$$

and

$$h_o = C_oZ. \qquad \textbf{(4.19)}$$

Substituting equations (4.18) and (4.19) into equation (4.9) yields

$$\frac{1}{U_oA_o} = \frac{1}{C_i\Omega A_i} + R_w + \frac{1}{C_oZA_o}. \qquad \textbf{(4.20)}$$

Rearranging gives

$$Y = mX + b \tag{4.21}$$

where

$$Y = \left(\frac{1}{U_o} - R_w A_o\right) Z, \tag{4.22}$$

$$X = \frac{A_o Z}{A_i \Omega}, \tag{4.23}$$

$$m = \frac{1}{C_i}, \tag{4.24}$$

and

$$b = \frac{1}{C_o}. \tag{4.25}$$

A least-squares fit of equation (4.21) with respect to X and Y gives the slope and intercept which are the reciprocals of C_i and C_o respectively. The accuracy of the modified Wilson plot technique is dependent on the number and spread of X-Y data points. With C_i and C_o now known, h_i and h_o for any data point follow from equations (4.18) and (4.19), and the temperature drop across the condensate film (ΔT_{film}) simply becomes

$$\Delta T_{film} = \frac{q''}{h_o}. \tag{4.26}$$

C. OUTSIDE HEAT TRANSFER CORRELATIONS

The first work on the study of filmwise condensation on horizontal smooth tubes was carried out by Nusselt [Ref. 4], as discussed in detail in Chapter 2. The average outside heat transfer coefficient for the Nusselt theory is given by

$$h_o = 0.728 \left[\frac{k_f^3 g \rho_f (\rho_f - \rho_v) \acute{h}_{fg}}{\mu_f D_o (T_{sat} - T_{wo})}\right]^{1/4}. \tag{4.27}$$

The Nusselt theory has been extensively studied, and with the imposed assumptions, it has been found to be generally valid [Refs. 45, 46]. It has also been found to be quite accurate for cases which do not conform to Nusselt's original assumptions, such as variable wall temperature [Ref. 47].

One of the major problems encountered in applying Nusselt's theory in the design of condensers arises from his assumption of a quiescent vapor. While in theory, and in some limited practical applications, the assumption of a stationary vapor can be justified, most steam condensers operate under conditions where the vapor is traveling at some sizable velocity. The downward flowing vapor introduces condensate thinning by vapor shear, which significantly increases the outside heat transfer coefficient beyond that predicted by Nusselt. Shekriladze and Gomelauri [Ref. 48] were the first to conduct a theoretical analysis to account for vapor shear. They assumed that the primary contribution to the surface shear stress was due to the change in momentum across the liquid-vapor interface. They approximated the mean Nusselt number (dimensionless mean heat transfer coefficient) as

$$\frac{Nu}{\sqrt{Re_{2\phi}}} = 0.64[1+(1+1.69F)^{1/2}]^{1/2} \qquad \textbf{(4.28)}$$

where the dimensionless parameter (F) is the ratio of the gravity force to the shear force,

$$F = \frac{gD_o\mu_f h_{fg}}{U_\infty^2 k_f (T_{sat}-T_{wo})} \qquad \textbf{(4.29)}$$

and $Re_{2\phi}$ is the two phase Reynolds number given by

$$Re_{2\phi} = \frac{\rho_f U_\infty D_o}{\mu_f}. \qquad \textbf{(4.30)}$$

At large values of F, where gravitational forces dominate, the Shekriladze and Gomelauri equation (4.28) reduces to Nusselt's equation (4.27). At low values of F, the

Shekriladze and Gomelauri correlation predicts significantly larger values of h_o than Nusselt due to the vapor shear thinning of the condensate film. Lee and Rose [Ref. 49] compared several vapor shear models with experimental results and found that the Shekriladze and Gomelauri results were more conservative than the more rigorous developments performed by other researchers due to their simplified approximation for the interfacial shear stress.

Fujii et al. [Ref. 50] developed an empirical formulation for the condensation of steam on a horizontal tube which included the vapor velocity effects. The Nusselt number for their model is given by

$$\frac{Nu}{Re_{2\phi}^{1/2}} = 0.96F^{1/5}, \tag{4.31}$$

where F and $Re_{2\phi}$ are defined in equations (4.29) and (4.30). For situations where the surface shear forces dominate, Fujii's correlation more accurately predicts the vapor side heat transfer coefficient for steam.

At NPS, Long [Ref. 34] processed his experimental data for steam velocities less than 2 m/s using both the Nusselt and Fujii correlations along with the modified Wilson plot technique. He found almost equal values of h_o, presumably due to the small amount of interfacial shear associated with these low velocities. Subsequent researchers at NPS have used Nusselt's outside correlation exclusively to avoid the necessity of calculating an accurate steam velocity. The leading coefficient in Nusselt's correlation is incorporated into C_o so that

$$Z = \left[\frac{k_f^3 g \rho_f^2 h_{fg}}{\mu_f D_r (T_{sat} - T_{wo})}\right]^{1/4}. \tag{4.32}$$

An iterative technique is used to find the film temperature (T_f) for evaluation of the properties and is described in Appendix C. The term on the right accounts for drainage from the tube as a function of the ratio of gravity to viscous forces. Heat transfer is a therefore a function of the drainage, thermophysical properties, temperature difference between steam and tube, and root diameter. Other factors that contribute to heat transfer such as area enhancement from finning, surface tension forces, and vapor shear are incorporated into the leading coefficient.

D. INSIDE HEAT TRANSFER CORRELATIONS

Several correlations are available for heat transfer within a smooth pipe with turbulent flow (Re > 10,000). A majority of the correlations are presented in the form

$$Nu = C_i Re^m Pr^n \tag{4.33}$$

which has been used for several well-known correlations including those developed by Dittus and Boelter [Ref. 51]

$$Nu = 0.023 Re^{0.8} Pr^{0.4} \tag{4.34}$$

and Colburn [Ref. 52]

$$Nu = 0.023 Re^{4/5} Pr^{1/3}. \tag{4.35}$$

A correction factor for equation (4.35) was developed by Sieder and Tate [Ref. 53] as

$$Nu = 0.027 Re^{4/5} Pr^{1/3} \left(\frac{\mu_c}{\mu_w} \right)^{0.14}, \tag{4.36}$$

to compensate for the variation in the coolant viscosity when large temperature differences exist between the bulk coolant and the inner tube wall temperatures. With the exception of μ_w, all coolant properties for equations (4.34), (4.35), and (4.36) are evaluated at the mean coolant bulk temperature (T_m)

$$T_m = \frac{T_1 + T_2}{2}. \tag{4.37}$$

The Dittus-Boelter, Colburn, and Sieder-Tate correlations are all valid for $Re > 10^4$ and $0.7 < Pr < 100$, and were developed for long, smooth pipes without inserts [Ref. 54].

More recently, Sleicher and Rouse [Ref. 55] and Petukhov and Popov [Ref. 56] developed equations which are applicable over a wider range of Prandtl numbers. The Sleicher-Rouse correlation is

$$Nu = 5 + 0.015 Re_f{}^c Pr_w{}^d \tag{4.38}$$

where

$$c = 0.88 - \frac{0.24}{4 + Pr_w} \tag{4.39}$$

and

$$d = \frac{1}{3} + 0.5\exp(-0.6 Pr_w). \tag{4.40}$$

The Petukhov-Popov correlation is

$$Nu = \frac{(\gamma/8) Re Pr}{K_1 + K_2 (\gamma/8)^{1/2} (Pr^{2/3} - 1)} \tag{4.41}$$

where

$$\gamma = (1.82 \log_{10}(Re) - 1.64)^{-2}, \tag{4.42}$$

$$K_1 = 1 + 3.4\gamma, \tag{4.43}$$

and

$$K_2 = 11.7 + 1.8 Pr^{-1/3}. \tag{4.44}$$

The Petukhov-Popov correlation is valid for $10^4 < Re < 5 \times 10^6$

and $0.5 < Pr < 2{,}000$.

At the Argonne National Laboratory, Lorenz et al. [Ref. 57] compared the experimentally determined inside Nusselt numbers for turbulent flow of cold water in smooth tubes to seven of the more common inside heat transfer correlations, namely, Dittus-Boelter, Sieder-Tate, Kays, Braun, Petukhov-Popov, Eagle-Ferguson, and Sleicher-Rouse. Tests were run at $Pr = 11.6$ with $10{,}000 < Re < 35{,}000$ and $Pr = 6.0$ with $40{,}000 < Re < 140{,}000$. They found that the Petukhov-Popov and Sleicher-Rouse correlations agreed with the experimentally determined inside Nusselt numbers within five percent. The other correlations typically underpredicted the data by up to 15 percent.

Both the Petukhov-Popov and Sleicher-Rouse correlations assume a long straight inlet section prior to the test section. Swenson [Ref. 32] identified these correlations as the most accurate but felt that he could not use them because of the 90° bend in the inlet flow arrangement for the test apparatus. O'Keefe [Ref. 33] used the modified Wilson plot technique and both of these inside correlations to analyze his data. He allowed the inside leading coefficient (C_i) to "float" in an iterative process. He then compared his values of h_o obtained using each inside correlation with Swenson's values of h_o obtained from an instrumented tube and found agreement within seven percent for smooth copper and titanium tubes. Using a recommendation of Lorenz [Ref. 57], he altered the Reynolds number exponent in the Sieder-Tate equation from 0.8 to 0.85, and obtained results similar to the Petukhov-Popov and Sleicher-Rouse correlations.

The Petukhov-Popov correlation requires determination of properties only at the coolant mean bulk temperature (T_m) while the Sieder-Tate and Sleicher-Rouse correlations require property evaluation at the inside wall temperature. Wall temperature must be iteratively determined when processing data from noninstrumented tubes. For this reason, the Petukhov-Popov correlation has been the choice of researchers at NPS since 1992 where

$$\Omega = \frac{k_w}{D_i} \times \frac{(\gamma/8)\,RePr}{K_1 + K_2(\gamma/8)^{1/2}(Pr^{2/3}-1)}\,. \tag{4.45}$$

The Petukhov-Popov correlation was derived for fully developed turbulent flow in smooth tubes with constant heat flux along the tube wall. No leading coefficient is required, so $h_i = \Omega$. During these tests, because of the 90° bend in the coolant line approximately 90 mm prior to the test tube and the use of an insert, the flow may be different than the conditions used in deriving the Petukhov-Popov correlation. In addition, because of a condensate film of varying thickness around the tube, heat flux is circumferentially variable. To account for these additional conditions, a leading coefficient (C_i) is introduced in equation (4.18).

E. ENHANCEMENT RATIO

The heat transfer enhancement ($\epsilon_{\Delta T}$) used in this thesis is the same as defined by Rose [Refs. 26, 27]. It is the ratio of heat transfer coefficients of a finned tube based on a smooth tube area of fin root diameter (D_r) to that of a smooth tube of outside diameter (D_o) equal to the finned tube root diameter. Both heat transfer coefficients are evaluated at the same vapor side temperature difference. Recalling that $h_o = C_o Z$,

$$\epsilon_{\Delta T} = \left(\frac{h_{o,finned}}{h_{o,smooth}}\right)_{\Delta T} = \left(\frac{C_{o,finned} Z_{finned}}{C_{o,smooth} Z_{smooth}}\right)_{\Delta T}. \tag{4.46}$$

For the same temperature drop across the condensate film, the film temperature and fluid properties are the same, so that $Z_{smooth} = Z_{finned}$ and equation (4.46) reduces to

$$\epsilon_{\Delta T} = \frac{C_{o,finned}}{C_{o,smooth}}. \tag{4.47}$$

From a previous discussion, C_o is probably a function of area enhancement and fin geometrical effects, surface tension effects, and vapor shear effects. No attempt was made during this thesis to separate out the individual contributions.

V. RESULTS AND DISCUSSION

A. RETEST OF MEYER'S STAINLESS STEEL TUBES

Due to the discrepencies in tube dimensions and program coding discussed in Chapter III and Appendix C, Meyer's stainless-steel tube data were reprocessed. The reported and reprocessed values of enhancement are shown in Tables 5.1 and 5.2. Because the effects of each discrepency are small, only minor differences between the two are noted. The trend of decreasing enhancement with increasing fin height remained the same. Reprocessing of the stainless steel, 1.12 mm fin height tube at vacuum conditions was not possible because his raw data file could not be located. Enhancements were determined from equation (4.89) where $C_{o,smooth}$ was obtained as the average of Cobb's [Ref. 6] smooth tube copper C_o values. These smooth tube values were 0.81 and 0.85 for vacuum and atmospheric trials, respectively.

Meyer's stainless steel tubes were retested under vacuum and atmospheric conditions. Two tests at each pressure condition were conducted for the tubes with 0.60 mm and 1.46 mm fin heights. Only one test was conducted at each pressure condition for the other tubes. Results are tabulated in Tables 5.3 and 5.4. Enhancement versus fin height is plotted in Figures 5.1 and 5.2 for Meyer's data and the retested values. The experimentally determined enhancements agreed within -11.0 to +8.7 percent except for the 0.60 fin height atmospheric trial which differed by -19.2 percent. Within the range of fin heights tested, the general trend of decreasing enhancement with increasing fin height noted by Meyer was confirmed.

Closer agreement with Meyer's enhancements was expected. Meyer only reported one trial for each tube at each test condition so it is possible that several of his trials could have been inaccurate. It was also thought that the difference

Material	Fin Height (mm)	Reported Enhancement	Reprocessed Enhancement	Percent Difference
STS	0.42	1.20	1.18	-1.4
STS	0.60	1.12	1.10	-1.6
STS	1.02	0.97	0.96	-0.2
STS	1.12	0.91	N.A.	N.A.
STS	1.46	0.96	0.94	-2.3

Table 5.1. Reported and Reprocessed Values of Enhancement for Meyer's Tubes (Vacuum)

Material	Fin Height (mm)	Reported Enhancement	Reprocessed Enhancement	Percent Difference
STS	0.42	1.36	1.34	-1.3
STS	0.60	1.14	1.42	0.1
STS	1.02	1.14	1.14	-0.2
STS	1.12	1.17	1.10	-5.5
STS	1.46	1.10	1.07	-3.4

Table 5.2. Reported and Reprocessed Values of Enhancement for Meyer's Tubes (Atmospheric)

Fin Height (mm)	Meyer's Results			Retest Results		
	C_i	C_o	Enhancement	C_i	C_o	Enhancement
0.42	2.34	0.96	1.18	2.33	1.00	1.24
0.60	2.58	0.89	1.10	2.08	0.78	0.96
				2.45	0.81	1.00
1.02	2.21	0.78	0.96	2.07	0.73	0.90
1.12	File not available			1.85	0.74	0.91
1.46	1.95	0.76	0.94	1.81	0.76	0.94
				2.09	0.74	0.91

Table 5.3. Comparison of the Experimentally Determined Values of C_i, C_o, and Enhancement for Meyer's Stainless Steel Tubes (Vacuum)

Fin Height (mm)	Meyer's Results			Retest Results		
	C_i	C_o	Enhancement	C_i	C_o	Enhancement
0.42	2.69	1.15	1.34	2.58	1.24	1.46
0.60	3.06	1.22	1.42	2.32	0.98	1.15
				2.75	0.98	1.15
1.02	2.42	0.98	1.14	2.15	0.94	1.11
1.12	2.87	0.95	1.10	2.17	0.97	1.14
1.46	2.50	0.92	1.07	2.17	1.02	1.20
				2.35	0.98	1.15

Table 5.4. Comparison of the Experimentally Determined Values of C_i, C_o, and Enhancement for Meyer's Stainless Steel Tubes (Atmospheric)

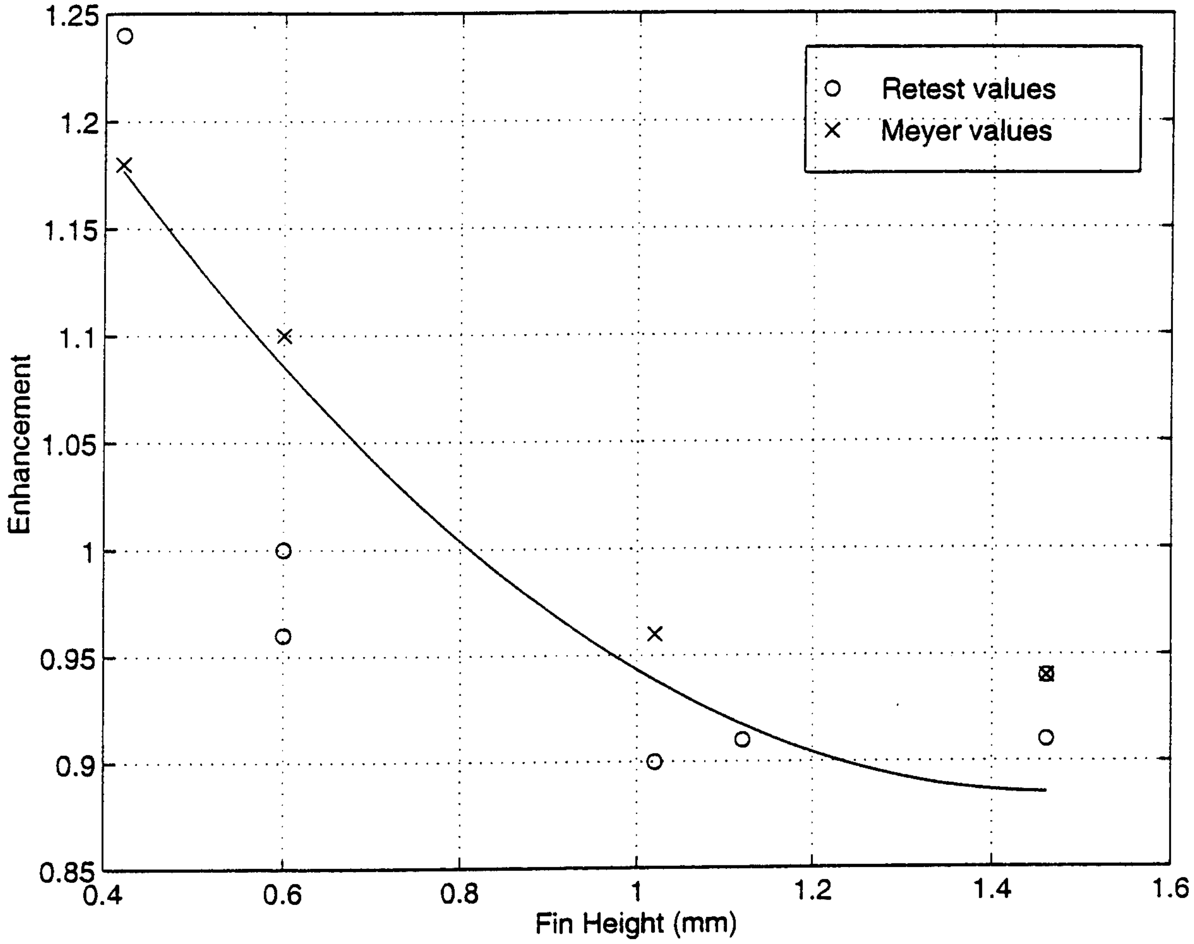

Figure 5.1. Meyer's and the Retested Experimental Values for Enhancement vs. Fin Height for Stainless Steel Integral-Fin Tubes (Vacuum)

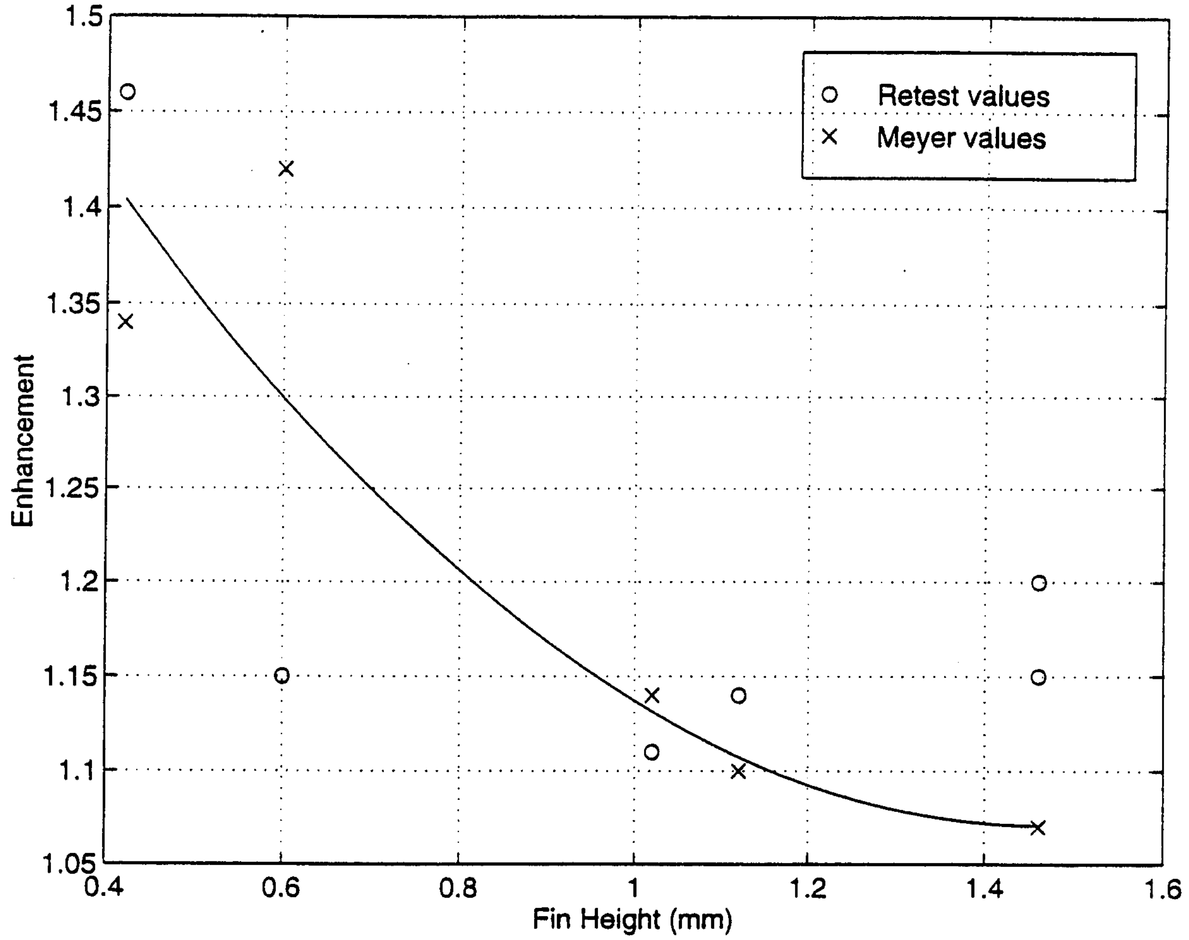

Figure 5.2 Meyer's and the Retested Experimental Values for Enhancement vs. Fin Height for Stainless Steel Integral-Fin Tubes (Atmospheric)

could be attributed to differences in coolant temperature rise. Because of seasonal variations in the ground temperature, Meyer's coolant inlet temperatures were 1° to 2°C lower than when the retests were conducted. The temperature difference between steam and coolant was thus larger for his trials, resulting in a larger coolant temperature rise through the tube. In addition, it was later found that the retesting of Meyer's tubes was accomplished with the HEATEX insert installed backwards [Ref. 42]. Consequently, the coolant temperature rise would not be as large. Whether due to greater inlet temperature or due to reverse positioning of the insert, smaller coolant temperature rises, and hence smaller heat fluxes, could have clustered the X-Y data points on the modified Wilson plot, lending to an imprecisely determined value of C_o. The insert was correctly installed for the second trials conducted on the 0.60 mm and 1.46 mm fin height tubes. The coolant temperature rise was slightly larger for these trials, however, little change was observed in the value of C_o.

A comparison of the X-Y data points in the modified Wilson plot for an original Meyer experimental run and retests with the insert installed correctly and incorrectly is shown in Figure 5.3. Little difference is observed in the spread of points or the slope of the least-squares line for each trial, yet the intercepts (inverse of C_o) are different for each. More than likely, this difference in intercept and consequent values of C_o and enhancement, can be attributed solely to experimental uncertainty and not to differences in coolant temperature rise.

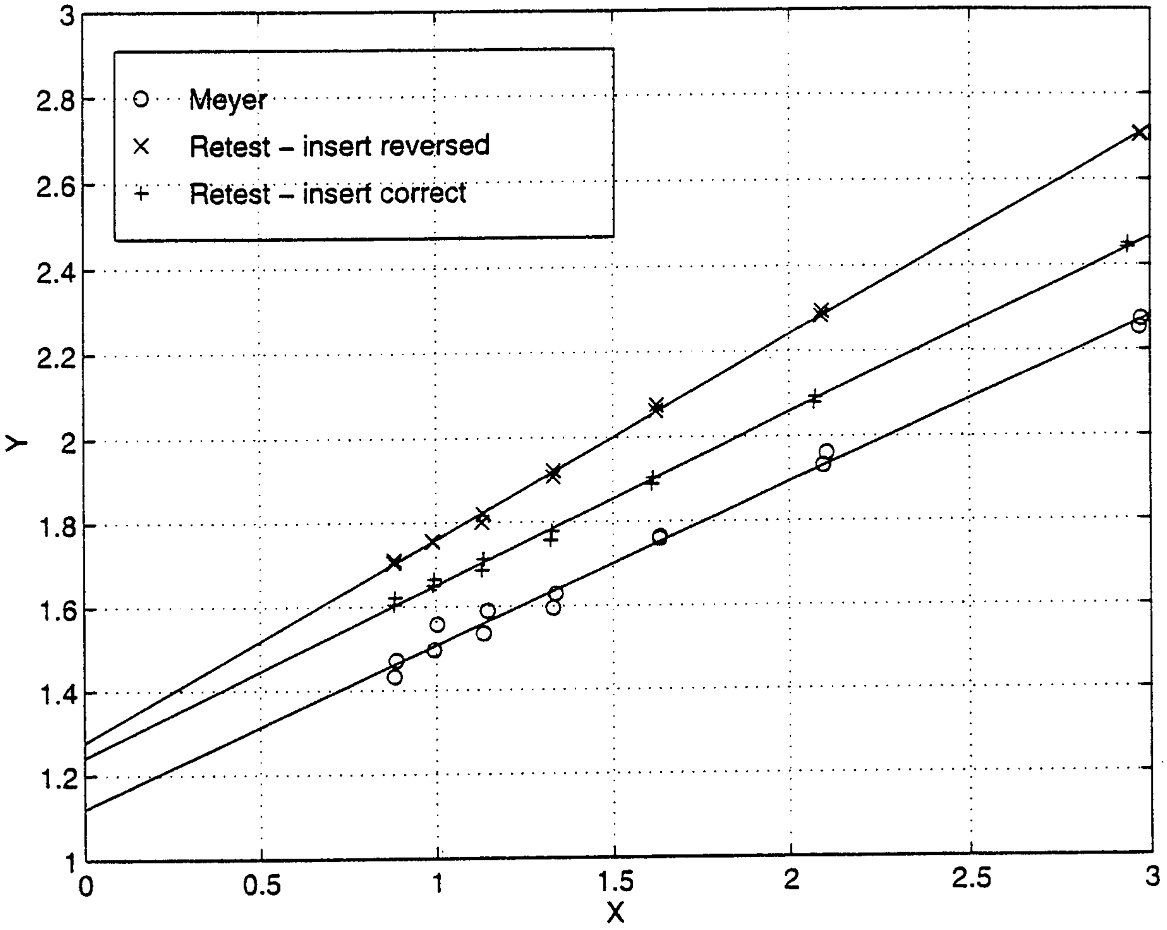

Figure 5.3 Comparison of Modified Wilson Plot Experimental Data for a 0.60 mm Fin Height Stainless Steel Tube Under Vacuum Conditions

B. TEST RESULTS OF THE NEW FAMILY OF STAINLESS STEEL TUBES

1. General Discussion

The nine newly fabricated stainless steel tubes were tested under vacuum and atmospheric conditions. An experimental trial was considered acceptable if no evidence of dropwise condensation was observed and if the system was maintained within the prescribed power and saturation temperature ranges. Two or three acceptable trials were conducted for each tube at each pressure condition. A total of 48 trials was accomplished with 40 judged acceptable. The minimum modified Wilson plot regression coefficient was 0.997. Most values exceeded 0.999. This indicates an excellent linear fit of the data points for determining the values of the leading heat transfer coefficients. Raw and processed data sheets are compiled in Appendix D.

Summaries of the experimentally determined enhancement and heat transfer correlation leading coefficients are shown in Tables 5.5 and 5.6. Enhancements were determined from equation (4.89) where $C_{o,smooth}$ was obtained by averaging the smooth tube C_o values from trials conducted at the same pressure condition. These average smooth tube values are 0.815 and 0.827 for vacuum and atmospheric trials, respectively, and are within a few percent of Cobb's [Ref. 6] smooth tube values. Comparisons of enhancements calculated for the same tube and pressure condition show a difference of less than 7.8 percent for vacuum conditions and less than 5.7 percent for atmospheric conditions. Repeatable results were therefore obtained.

2. Trends in Inside Heat Transfer Correlation Leading Coefficient, C_i

The purpose of the HEATEX insert is to increase the turbulence of the cooling water, remove the laminar sublayer, and enhance the inside heat transfer coefficient. Just as the

File Name	Fin Height (mm)	C_i	C_o	Enhancement
SSMTV3	Smooth	2.80	0.82	1.00
SSMTV4	Smooth	2.86	0.81	1.00
S16V1	0.16	2.71	1.09	1.34
S16V2	0.16	2.69	1.09	1.34
S28V1	0.28	2.67	1.17	1.44
S28V2	0.28	2.56	1.16	1.42
S28V3	0.28	2.61	1.13	1.39
S38V2	0.38	2.62	0.97	1.20
S38V3	0.38	2.63	0.99	1.21
S48V1	0.48	2.50	0.95	1.16
S48V2	0.48	2.50	0.97	1.19
S75V1	0.75	2.35	0.88	1.08
S75V2	0.75	2.17	0.84	1.03
S95V1	0.95	2.10	0.77	0.95
S95V2	0.95	2.21	0.83	1.02
S126V1	1.26	2.01	0.75	0.82
S126V2	1.26	2.08	0.76	0.83
S142V3	1.42	2.14	0.71	0.87
S142V4	1.42	2.07	0.73	0.89
S142V5	1.42	2.11	0.71	0.87

Table 5.5. Experimentally Determined Values of C_i, C_o, and Enhancement for New Stainless Steel Tubes (Vacuum)

File Name	Fin Height (mm)	C_i	C_o	Enhancement
SSMTA2	Smooth	3.01	0.83	1.00
SSMTA3	Smooth	3.01	0.83	1.00
S16A1	0.16	3.17	1.11	1.34
S16A2	0.16	3.10	1.12	1.35
S28A1	0.28	3.08	1.33	1.61
S28A2	0.28	2.95	1.28	1.55
S28A3	0.28	3.01	1.26	1.52
S38A1	0.38	2.95	1.09	1.31
S38A2	0.38	2.90	1.12	1.36
S48A1	0.48	2.85	1.11	1.34
S48A2	0.48	2.82	1.14	1.38
S75A1	0.75	2.61	1.03	1.25
S75A2	0.75	2.65	1.05	1.27
S95A1	0.95	2.47	1.02	1.23
S95A2	0.95	2.55	1.04	1.26
S126A2	1.26	2.32	0.93	1.12
S126A3	1.26	2.32	0.96	1.16
S142A3	1.42	2.43	0.86	1.04
S142A4	1.42	2.47	0.86	1.05
S142A5	1.42	2.48	0.89	1.07

Table 5.6. Experimentally Determined Values of C_i, C_o, and Enhancement for New Stainless Steel Tubes (Atmospheric)

outside leading coefficient (C_o) is a measure of enhancement on the outside of the tube, the inside leading coefficient (C_i) can be viewed as a measure of enhancement on the inside of the tube. (From Chapter 4, C_i also accounts for the developing flow in the tube leader and heat flux variations.) Without an insert, C_i for the Petukhov-Popov correlation would ideally be unity. With an insert installed, the value of C_i is increased. From Tables 5.5 and 5.6, the smooth tube experimental values of C_i is approximately 2.8 and 3.0 for vacuum and atmospheric pressure conditions, respectively.

As fin height increases, the condensate flooding angle decreases. This is shown in Figure 5.4, by plotting the flooding angle determined by equations (2.6) and (2.7) for a fin spacing of 1.5 mm and fin heights ranging from 0 to 1.5 mm. As the flooding angle decreases, a larger fraction of the tube is covered with thick condensate film, and less heat transfer occurs overall. This is illustrated in Figures 5.5 and 5.6, where heat flux is plotted against fin height. Considering only radial heat flow, the inside of the tube views the thick film region on the lower outside portion of the tube as insulated. Heat will mostly be convected from the upper inside surface of the tube where the film on the tube outside is thin. Therefore, as the flooding angle decreases, the effective convective inside area decreases. Because the inside heat transfer coefficient is calculated assuming the entire inside circumference is active, it will decrease due to this decreasing effective convective area as shown in Figure 5.7. The reduction in the inside heat transfer coefficient is due almost exclusively to the decrease in C_i shown in Figure 5.8. Increasing fin height thus causes C_i to decrease.

This same trend was observed by Zebrowski [Ref. 58] and Lester [Ref. 59]. They placed plastic insulators of the same angular area on the inside and outside of their tubes. As the angle was increased for both insulators, the inside heat

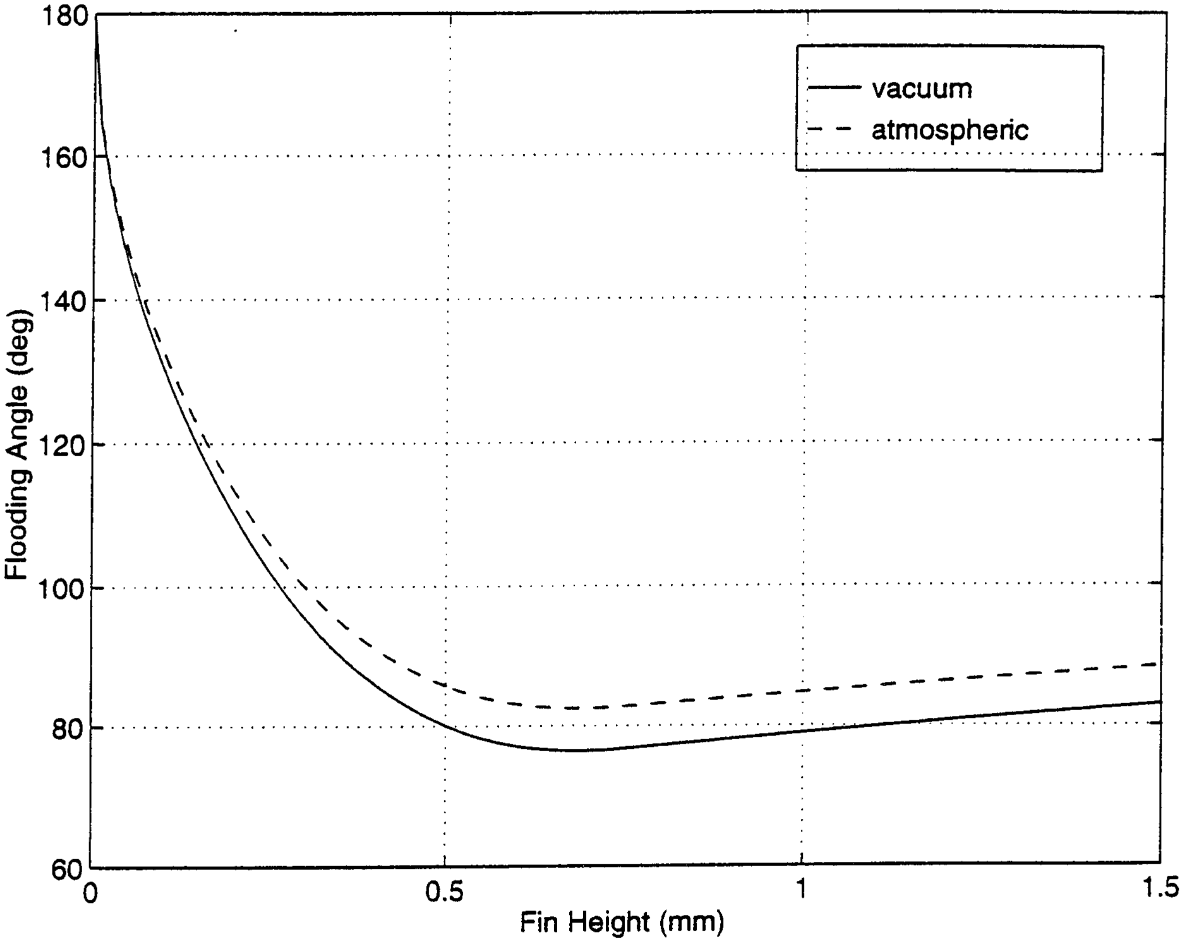

Figure 5.4 Analytically Determined Values of Flooding Angle vs. Fin Height for a Fin Spacing of 1.5 mm.

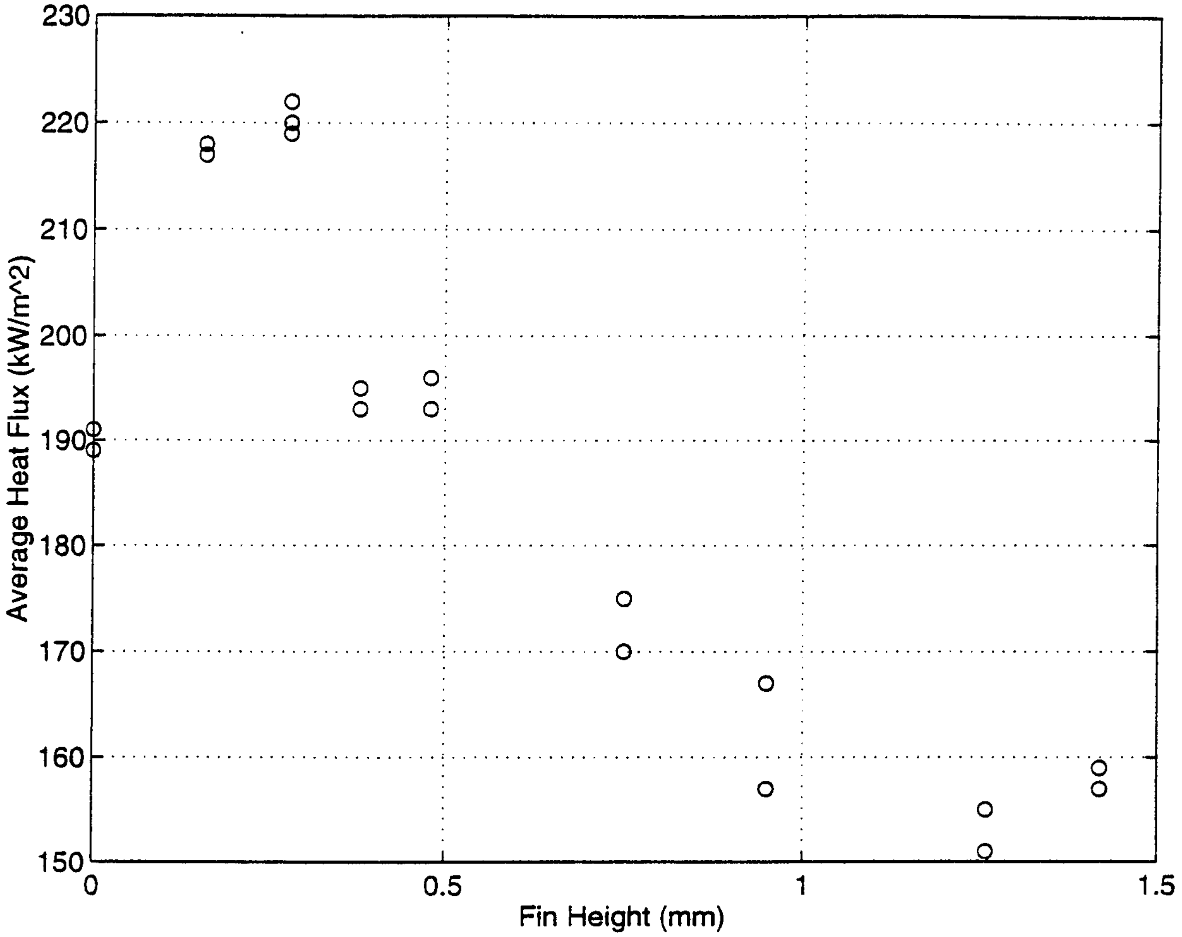

Figure 5.5 Comparison of Average Experimental Heat Flux and Fin Height for Stainless Steel Tubes (Vacuum)

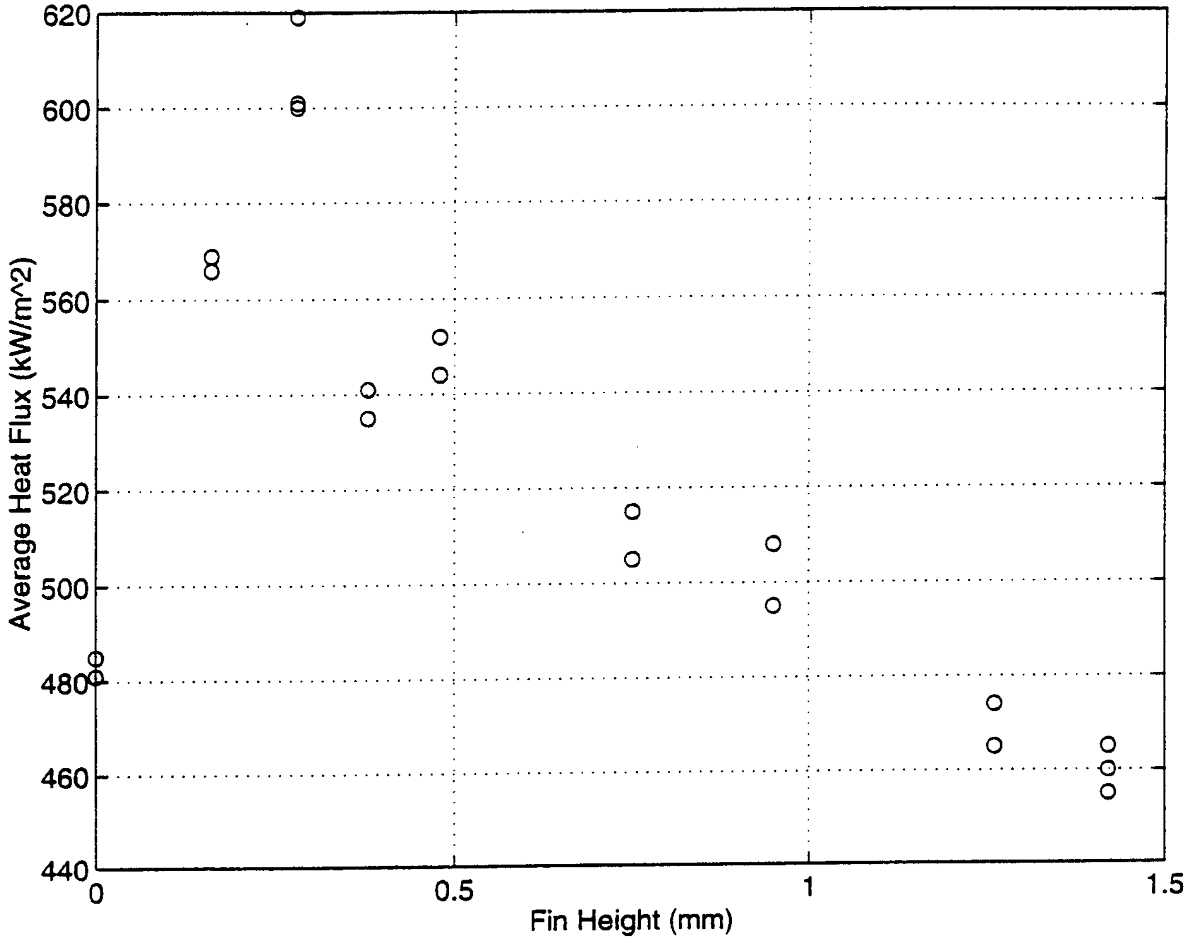

Figure 5.6 Comparison of Average Experimental Heat Flux and Fin Height for Stainless Steel Tubes (Atmospheric)

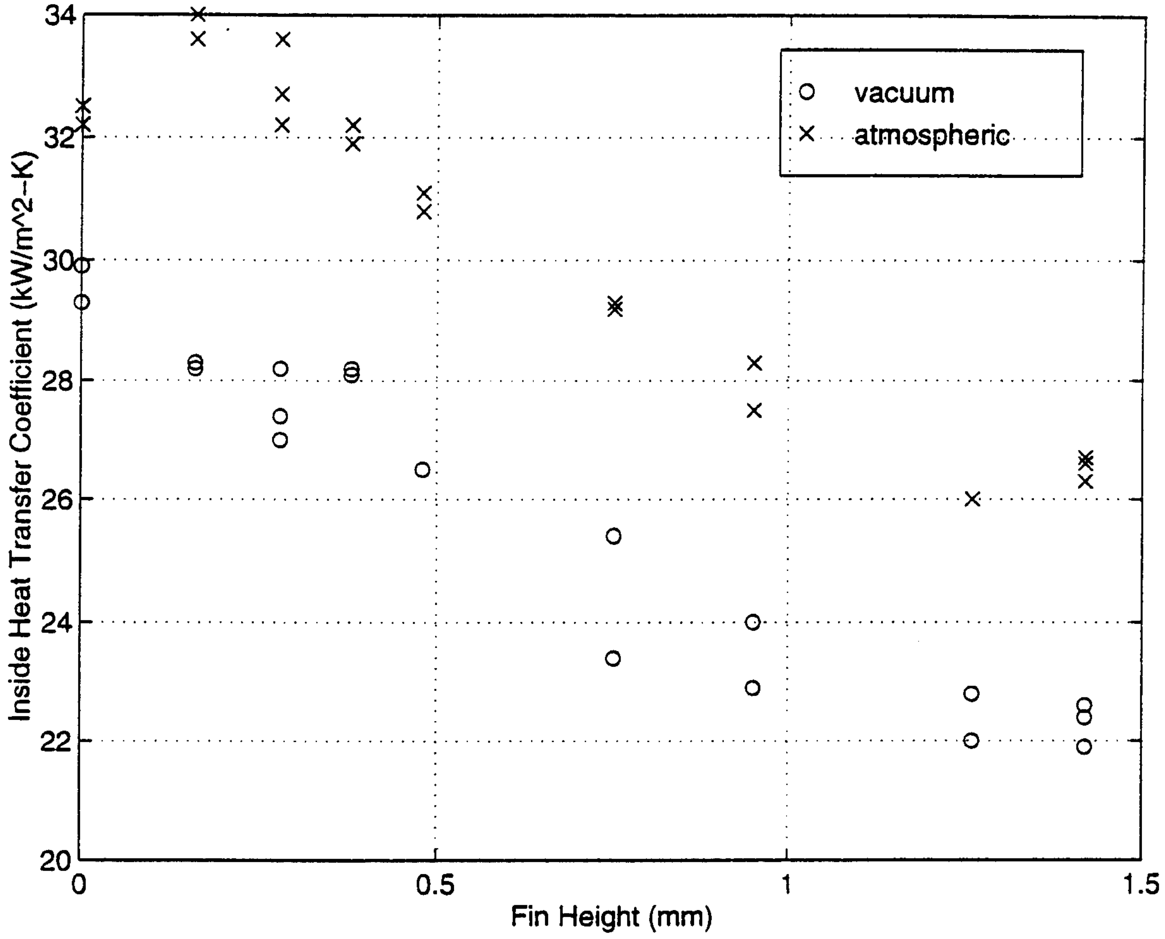

Figure 5.7 Comparison of Inside Heat Transfer Coefficient with Fin Height for Stainless Steel Tubes

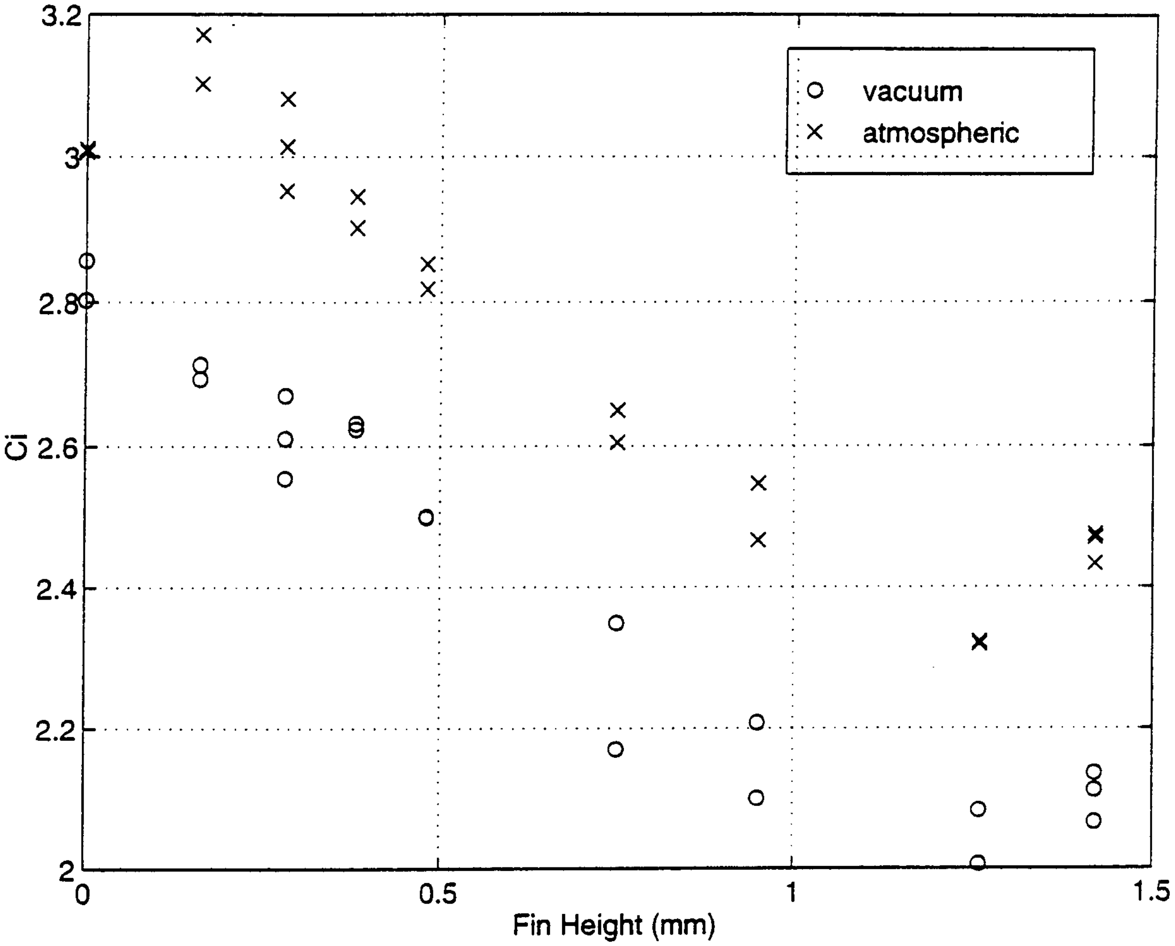

Figure 5.8 Comparison of the Leading Coefficient (C_i) of the Inside Heat Transfer Correlation with Fin Height for Stainless Steel Tubes

transfer coefficient and C_i decreased.

The Petukhov-Popov correlation was formulated for constant heat flux conditions circumferentially and axially. As pointed out in the preceding discussion, the condensation film thickness and heat flux vary around the tube. For this reason, the Petukhov-Popov correlation is probably more accurate for tubes of shorter fins where the flooding angle is larger and the angular heat flux distribution is small.

3. Comparison of Outside Heat Transfer Coefficient (h_o) with Condensate Film Temperature Drop

Plots of the outside heat transfer coefficients versus the temperature drop across the condensate film for each fin height and pressure condition are shown in Figures 5.9 through 5.26. The minimum and maximum experimental uncertainties are also plotted in the figures. These uncertainties in h_o and film ΔT were obtained from the uncertainty analysis described in Appendix E. Maximum uncertainties occurred at the highest coolant flow rates where the temperature rise of the coolant was least. Minimum uncertainties were obtained for the lowest flow rates where the coolant temperature rise was greatest. Uncertainties for the vacuum runs were greater than those for the atmospheric runs due to the smaller coolant temperature rise.

For all plots, the outside heat transfer coefficient is inversely related to the temperature drop across the condensate film. As the coolant flow rate is increased, the inside heat transfer coefficient and hence the heat flux increase. Increased condensation occurs, resulting in a thickening of the condensate film. Because the increased condensate thickness acts as an insulator and retards heat transfer, the temperature drop across the film increases and the outside heat transfer coefficient, which is inversely proportional to the film thickness, decreases. The temperature drop across the film is larger for the atmospheric

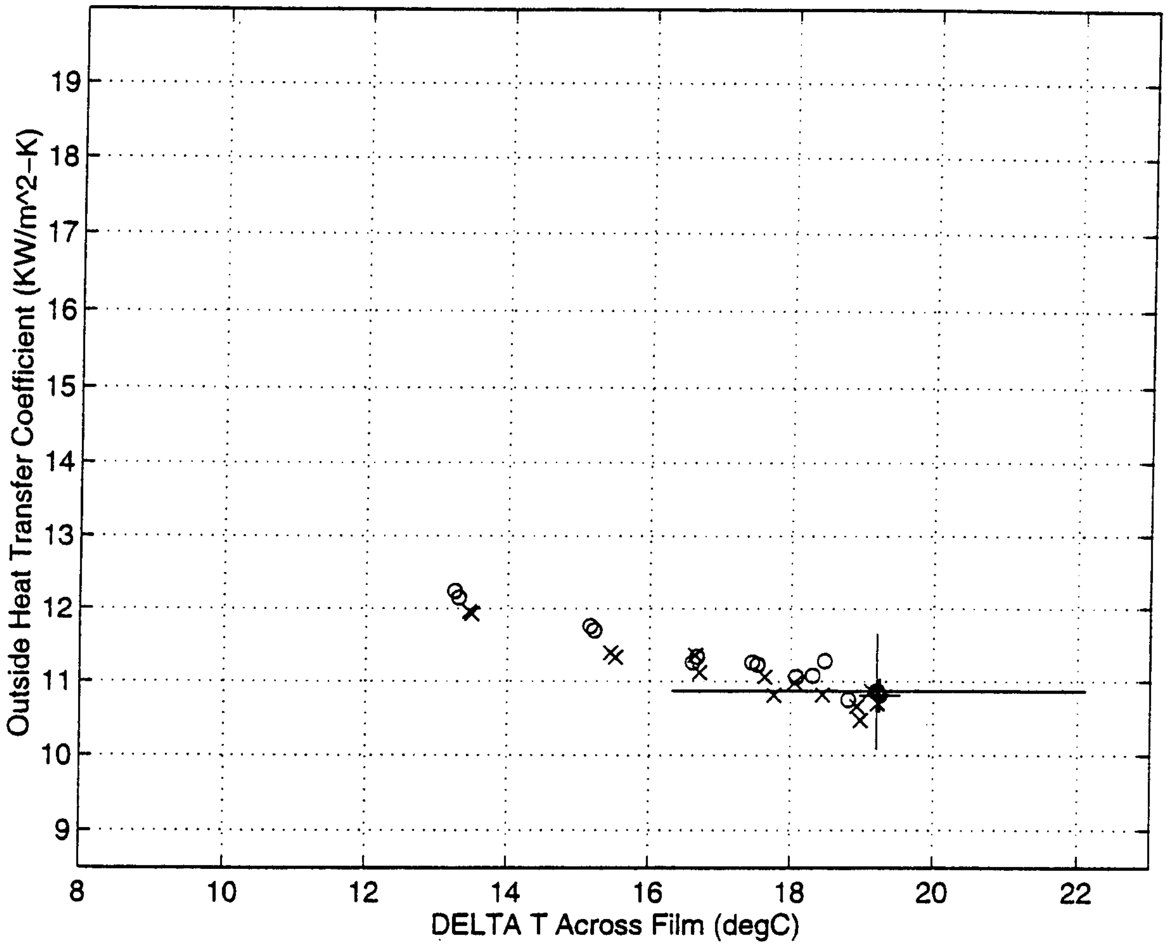

Figure 5.9 Experimentally Determined Values of the Outside Heat Transfer Coefficient vs. Film Temperature Difference for a Stainless Steel Smooth Tube (Vacuum)

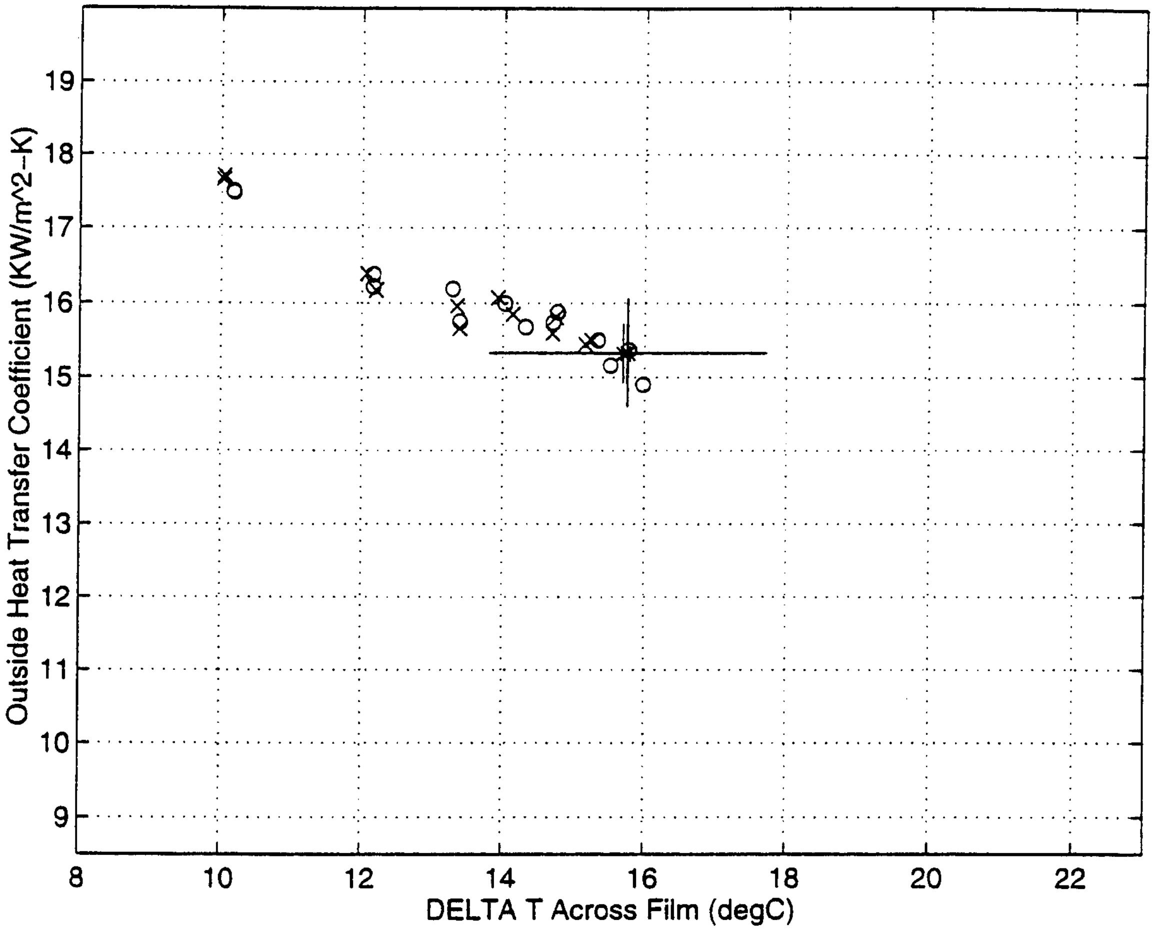

Figure 5.10 Experimentally Determined Values of the Outside Heat Transfer Coefficient vs. Film Temperature Difference for a Stainless Steel Integral-Fin Tube with Fin Height 0.16 mm (Vacuum)

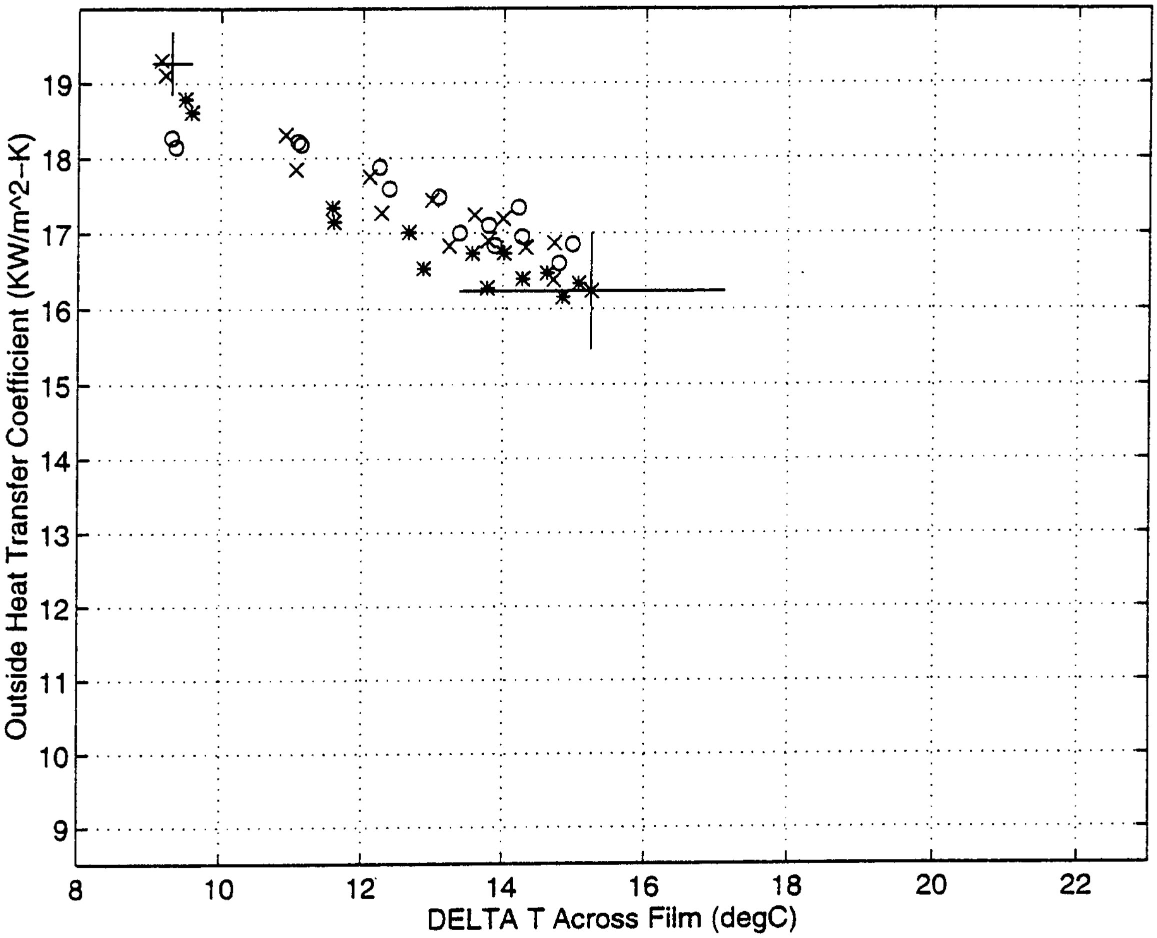

Figure 5.11 Experimentally Determined Values of the Outside Heat Transfer Coefficient vs. Film Temperature Difference for a Stainless Steel Integral-Fin Tube with Fin Height 0.28 mm (Vacuum)

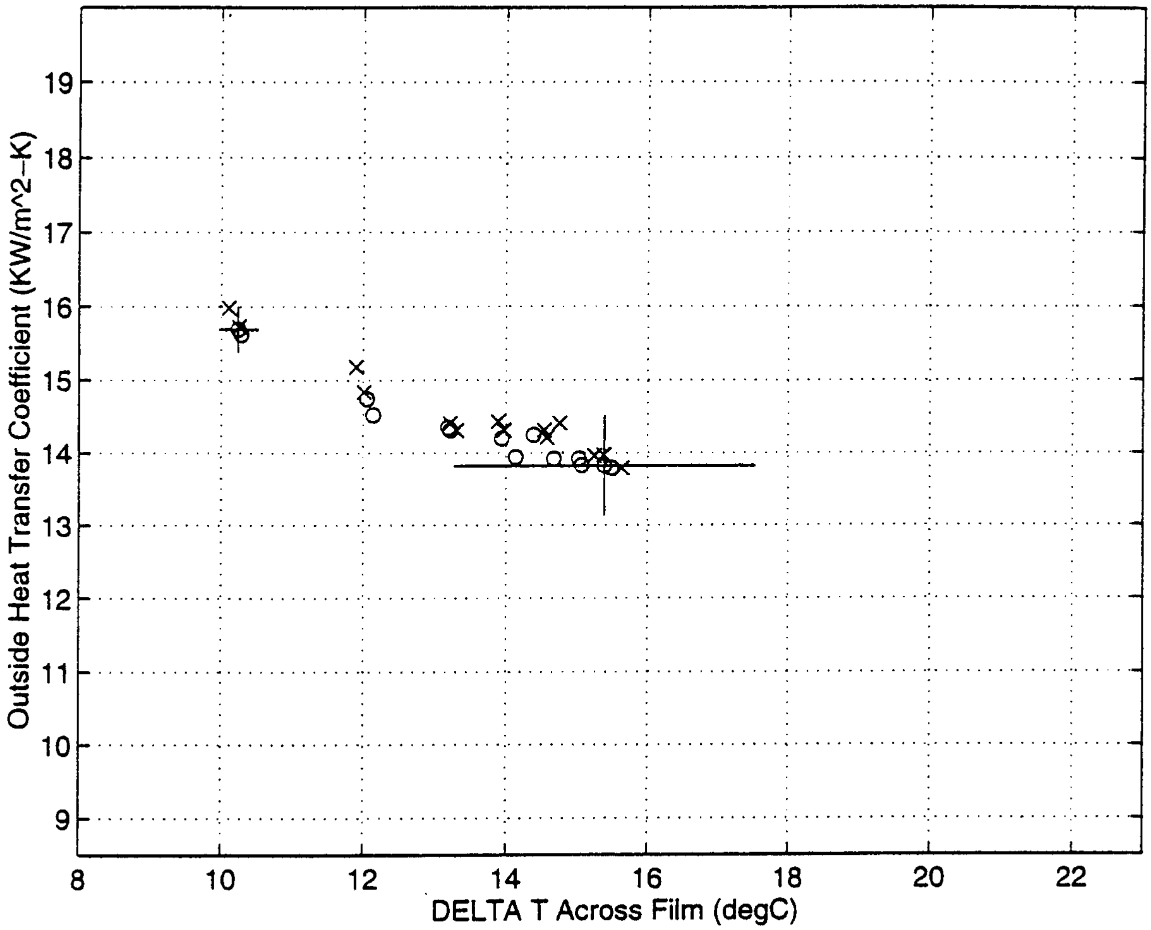

Figure 5.12 Experimentally Determined Values of the Outside Heat Transfer Coefficient vs. Film Temperature Difference for a Stainless Steel Integral-Fin Tube with Fin Height 0.38 mm (Vacuum)

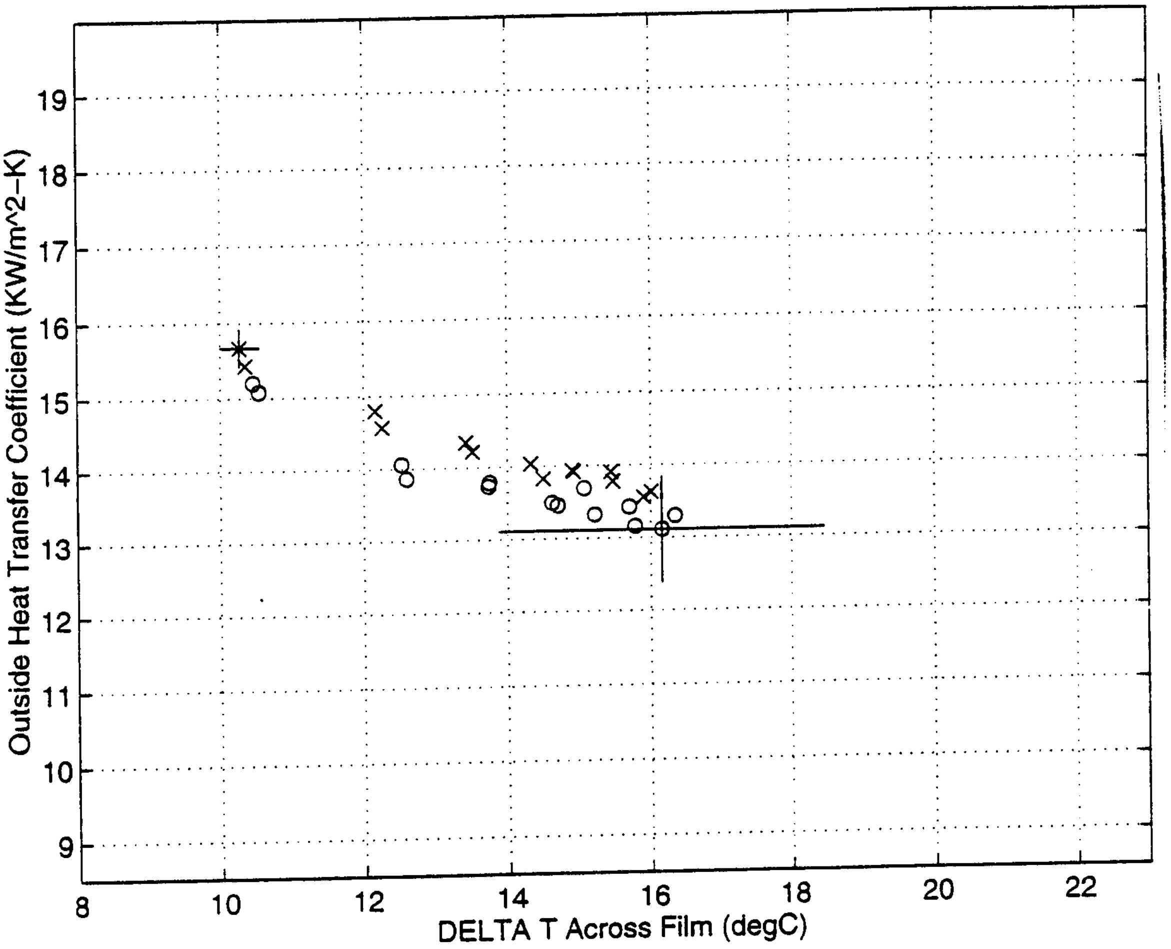

Figure 5.13 Experimentally Determined Values of the Outside Heat Transfer Coefficient vs. Film Temperature Difference for a Stainless Steel Integral-Fin Tube with Fin Height 0.48 mm (Vacuum)

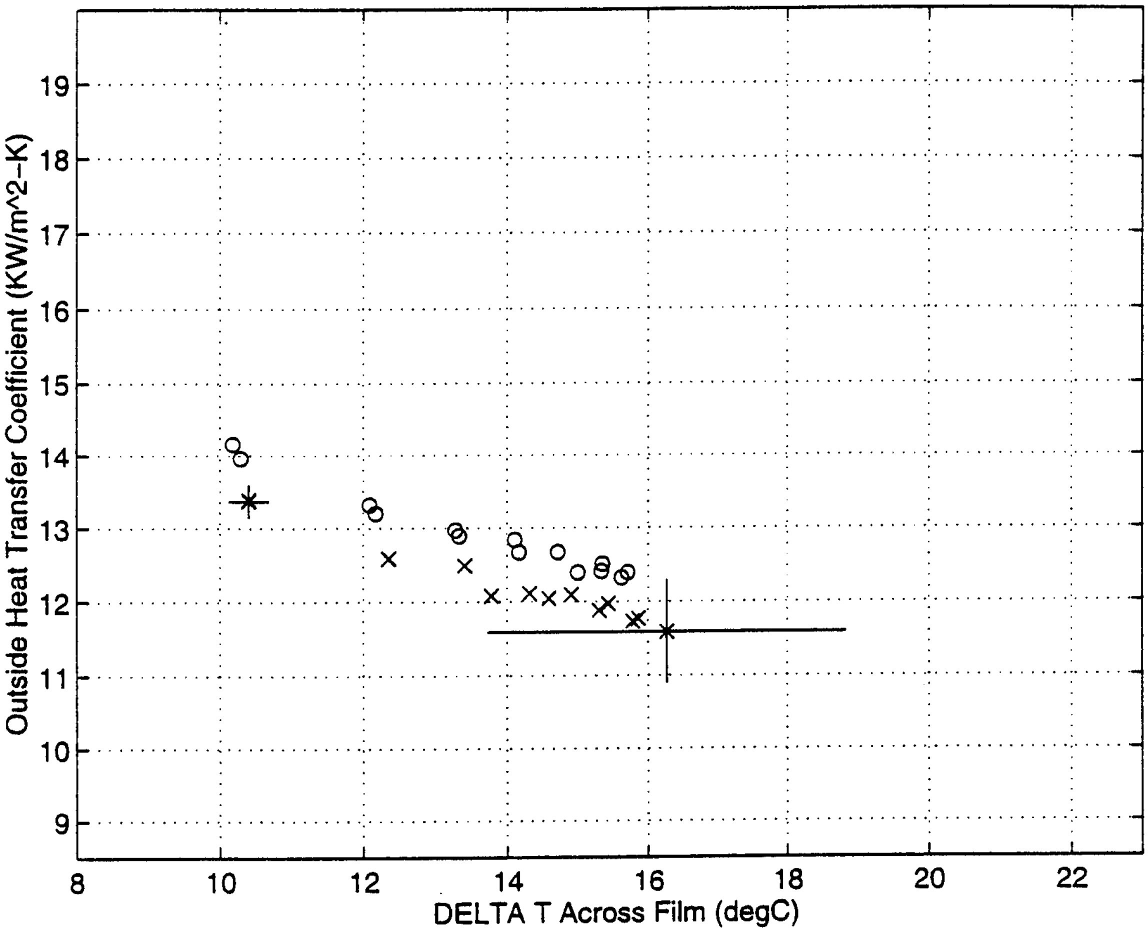

Figure 5.14 Experimentally Determined Values of the Outside Heat Transfer Coefficient vs. Film Temperature Difference for a Stainless Steel Integral-Fin Tube with Fin Height 0.75 mm (Vacuum)

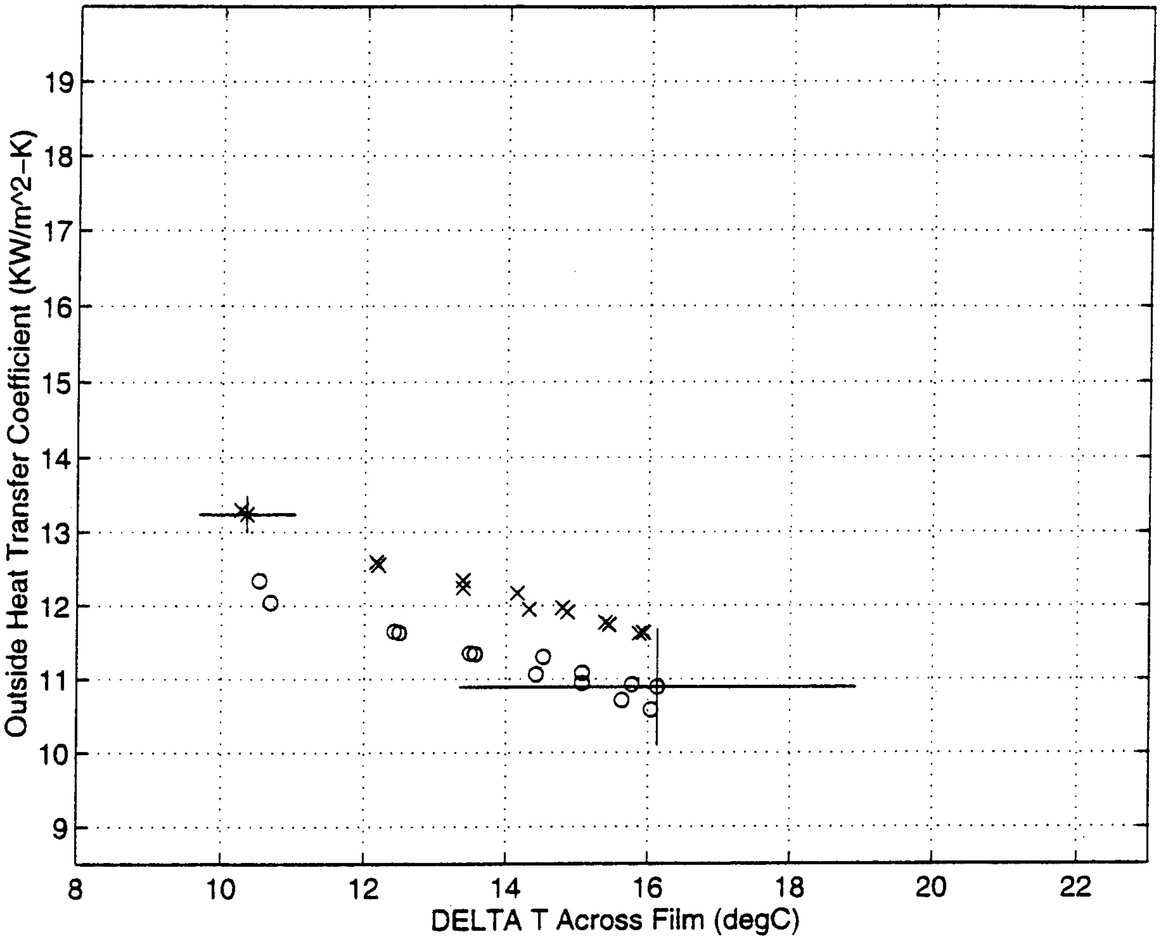

Figure 5.15 Experimentally Determined Values of the Outside Heat Transfer Coefficient vs. Film Temperature Difference for a Stainless Steel Integral-Fin Tube with Fin Height 0.95 mm (Vacuum)

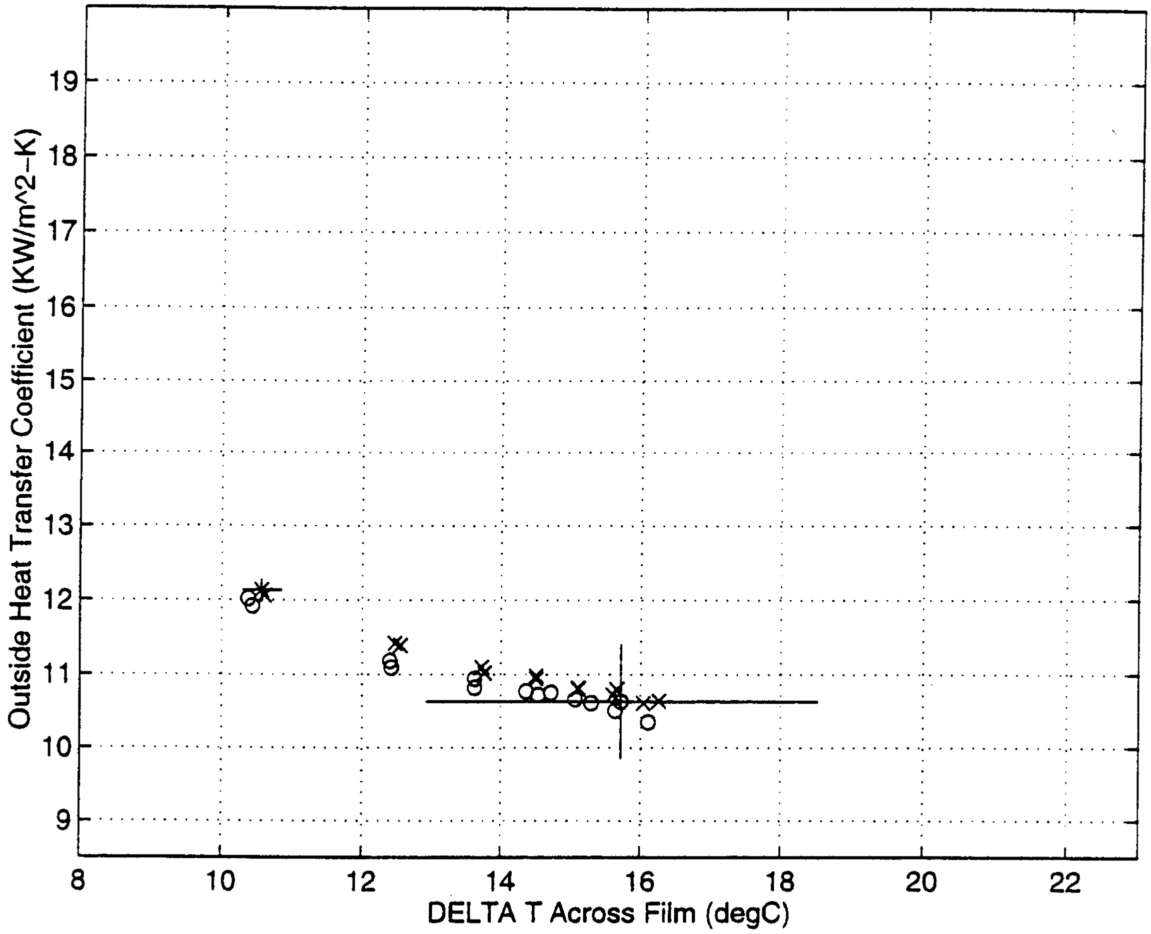

Figure 5.16 Experimentally Determined Values of the Outside Heat Transfer Coefficient vs. Film Temperature Difference for a Stainless Steel Integral-Fin Tube with Fin Height 1.26 mm (Vacuum)

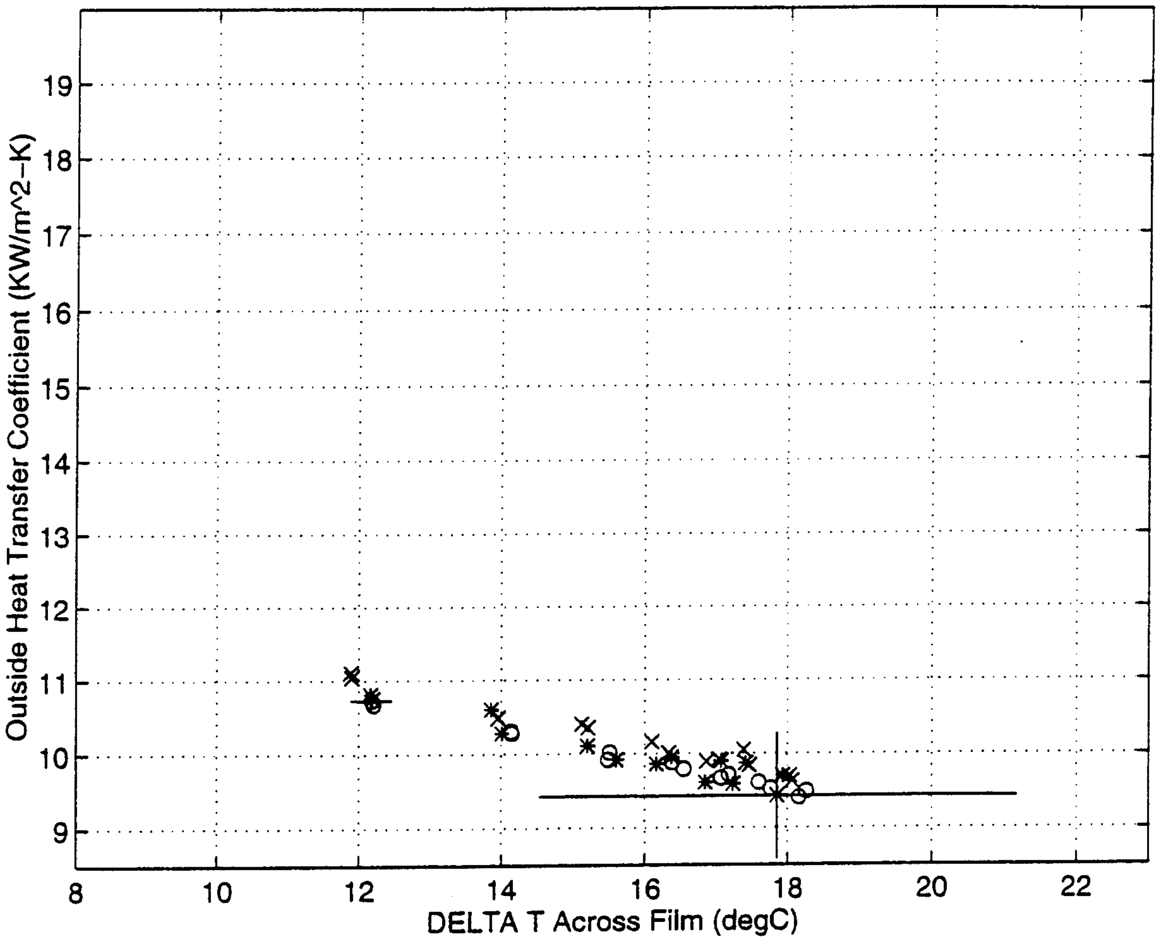

Figure 5.17 Experimentally Determined Values of the Outside Heat Transfer Coefficient vs. Film Temperature Difference for a Stainless Steel Integral-Fin Tube with Fin Height 1.42 mm (Vacuum)

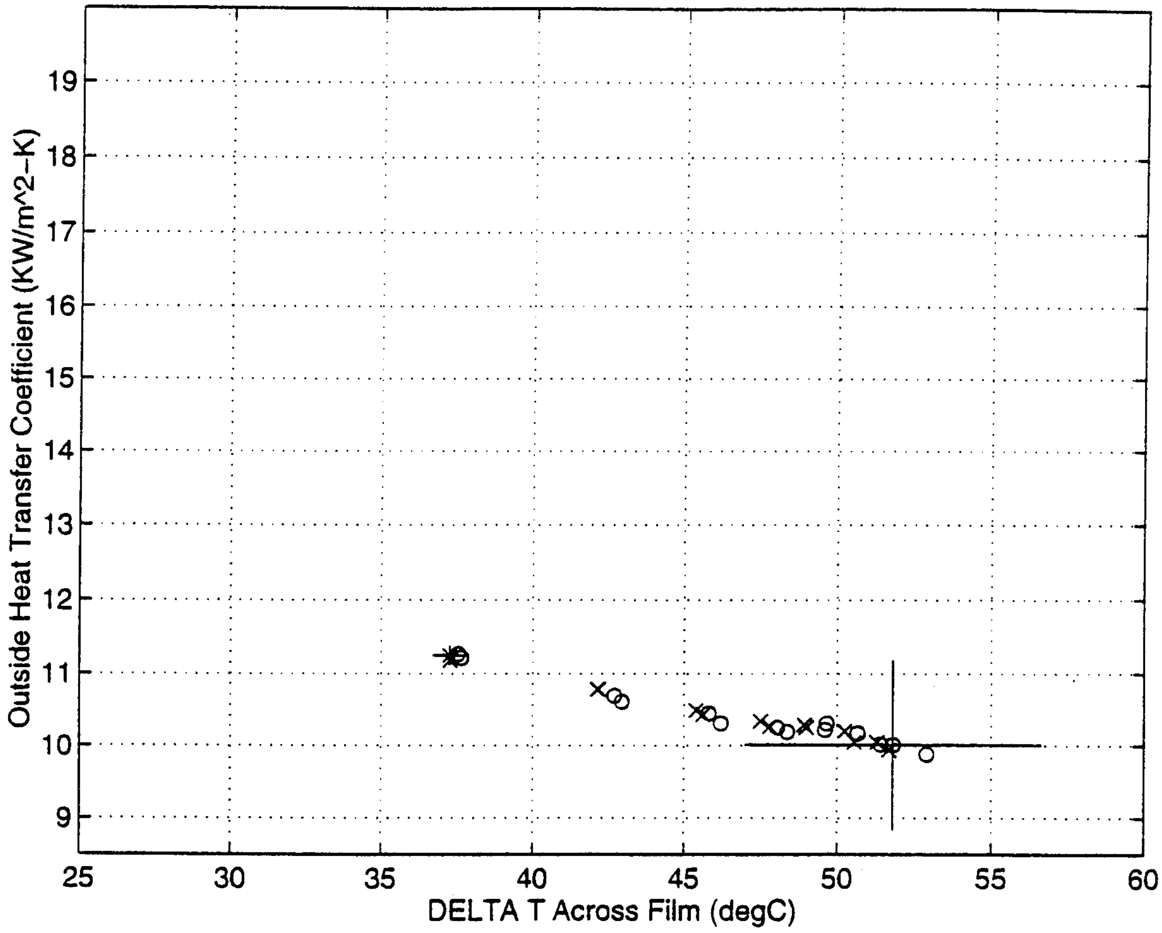

Figure 5.18 Experimentally Determined Values of the Outside Heat Transfer Coefficient vs. Film Temperature Difference for a Stainless Steel Smooth Tube (Atmospheric)

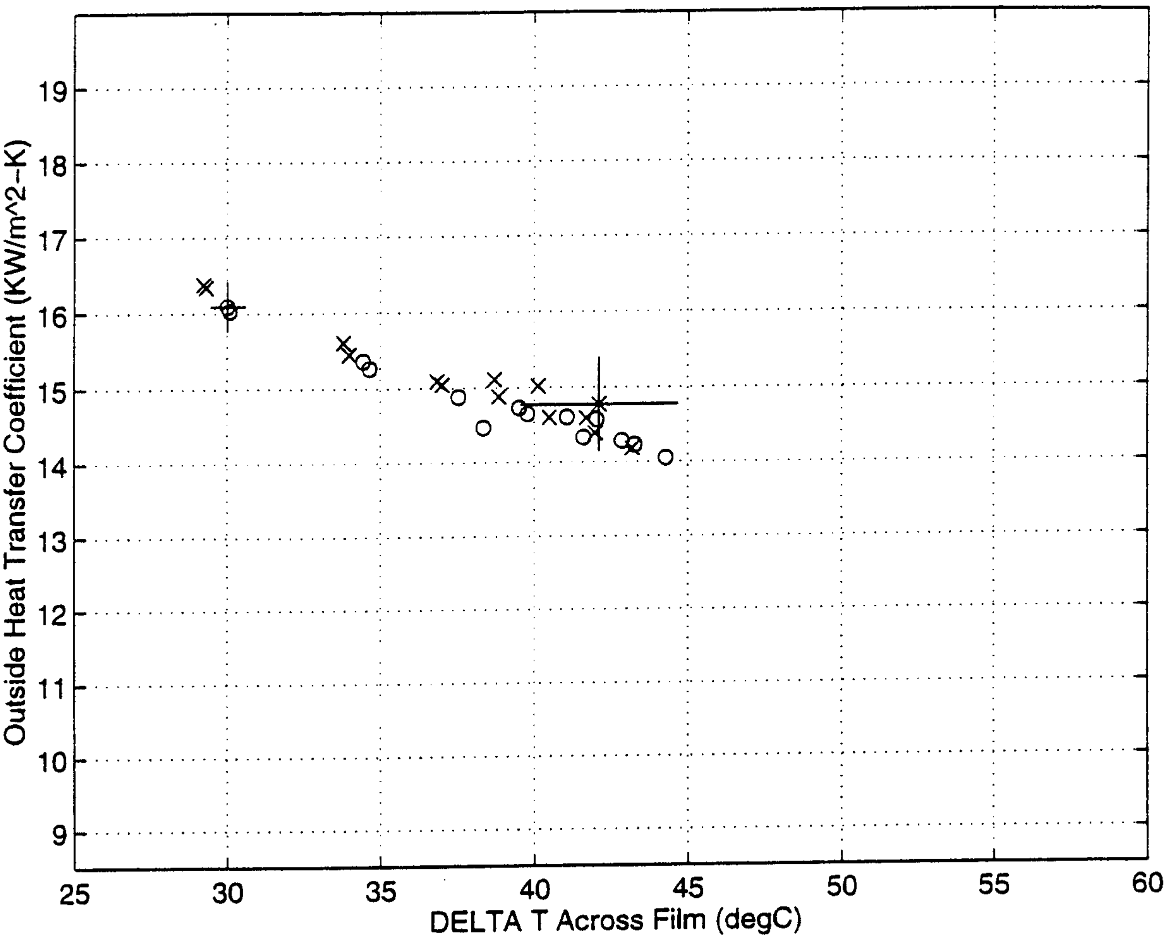

Figure 5.19 Experimentally Determined Values of the Outside Heat Transfer Coefficient vs. Film Temperature Difference for a Stainless Steel Integral-Fin Tube with Fin Height 0.16 mm (Atmospheric)

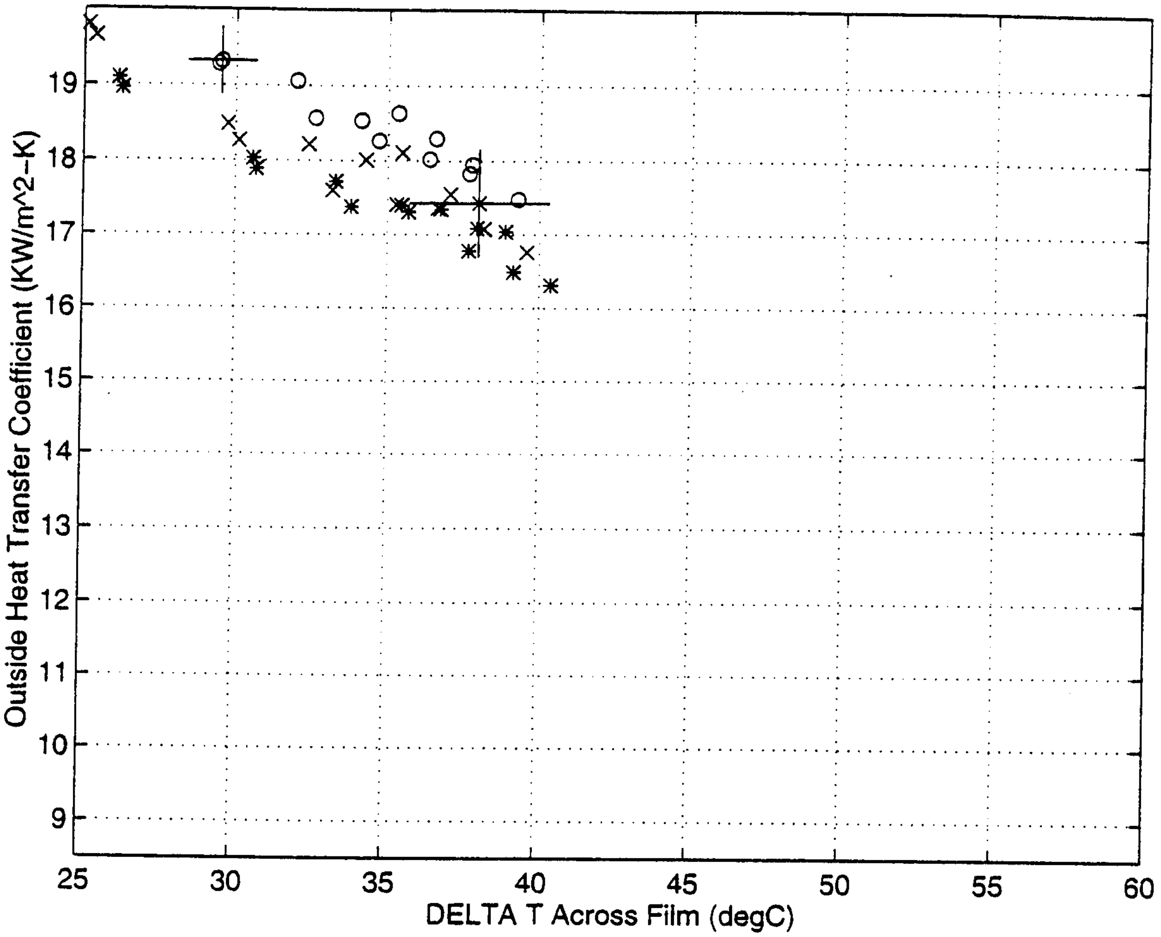

Figure 5.20 Experimentally Determined Values of the Outside Heat Transfer Coefficient vs. Film Temperature Difference for a Stainless Steel Integral-Fin Tube with Fin Height 0.28 mm (Atmospheric)

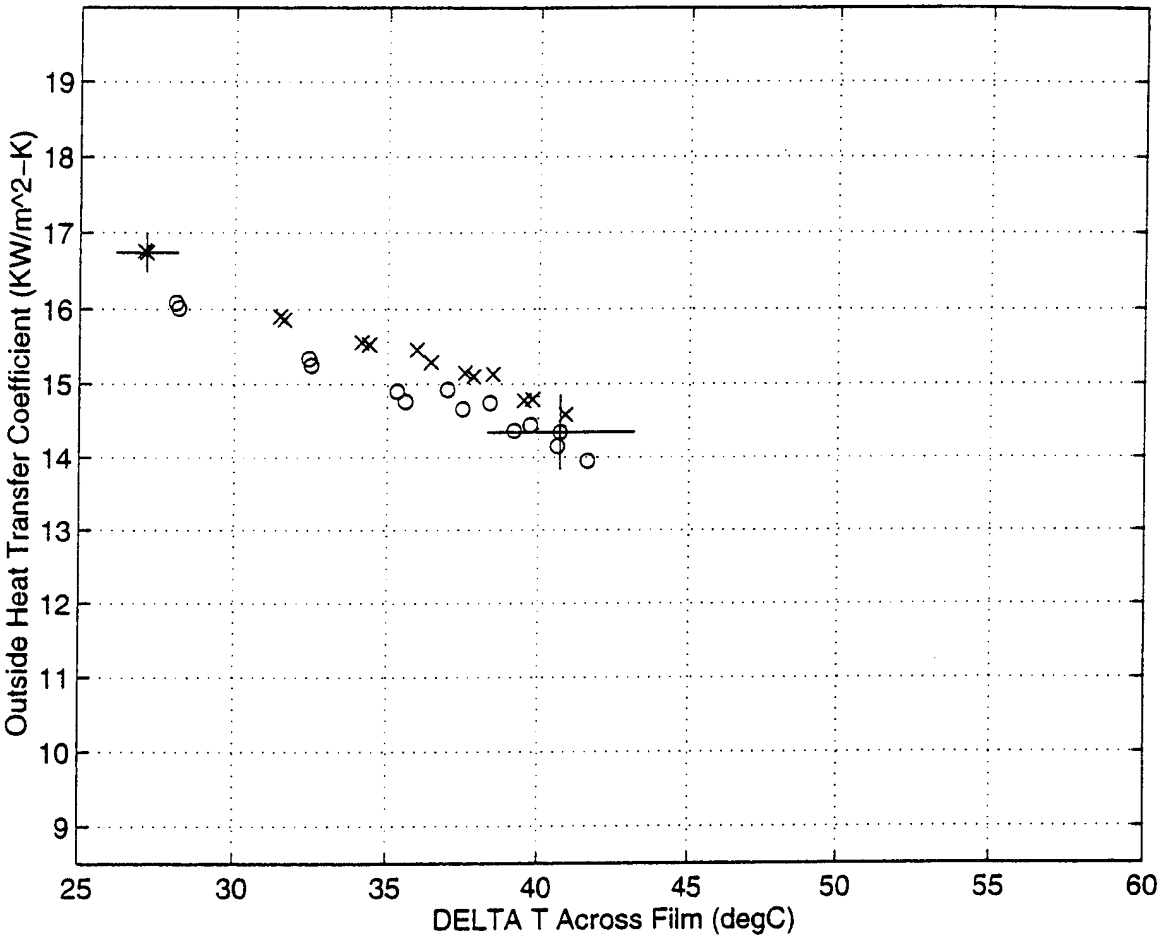

Figure 5.21 Experimentally Determined Values of the Outside Heat Transfer Coefficient vs. Film Temperature Difference for a Stainless Steel Integral-Fin Tube with Fin Height 0.38 mm (Atmospheric)

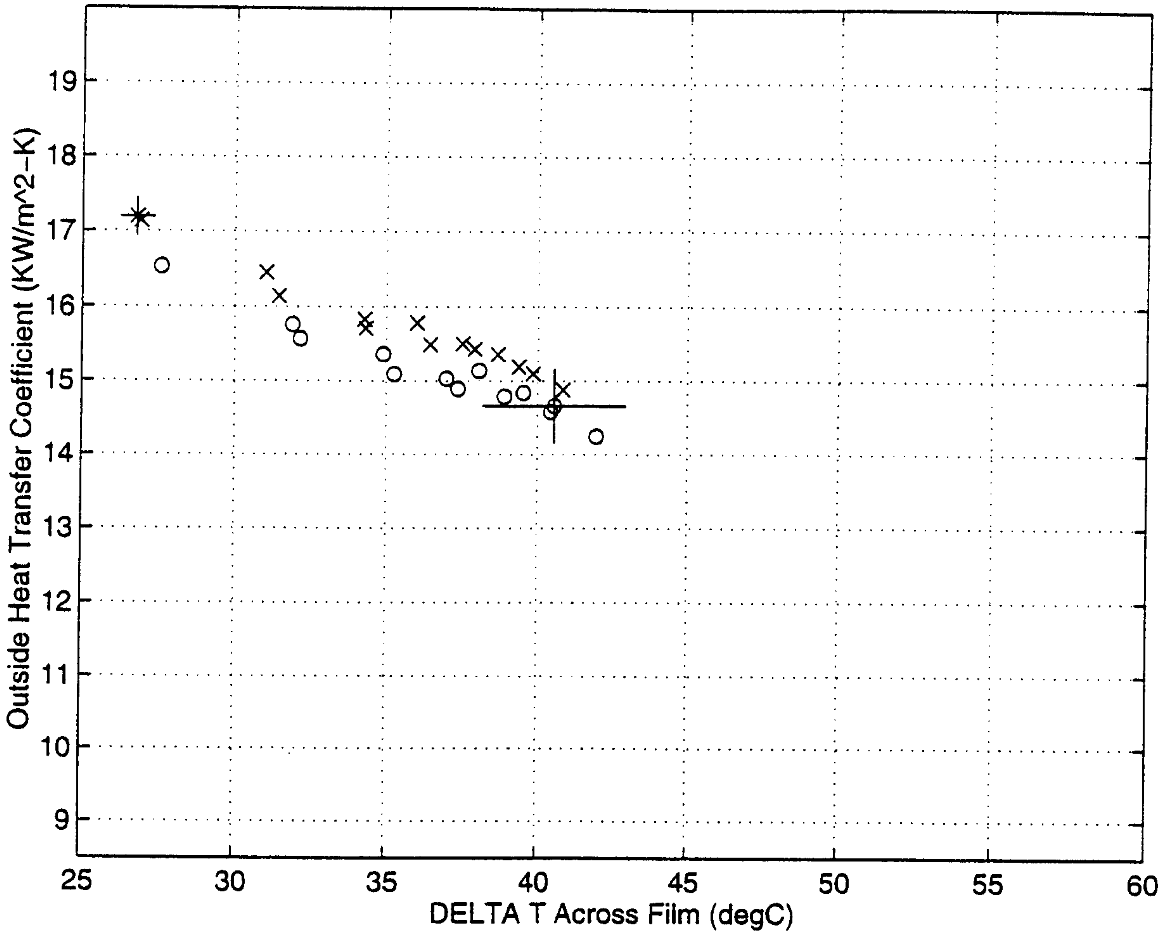

Figure 5.22 Experimentally Determined Values of the Outside Heat Transfer Coefficient vs. Film Temperature Difference for a Stainless Steel Integral-Fin Tube with Fin Height 0.48 mm (Atmospheric)

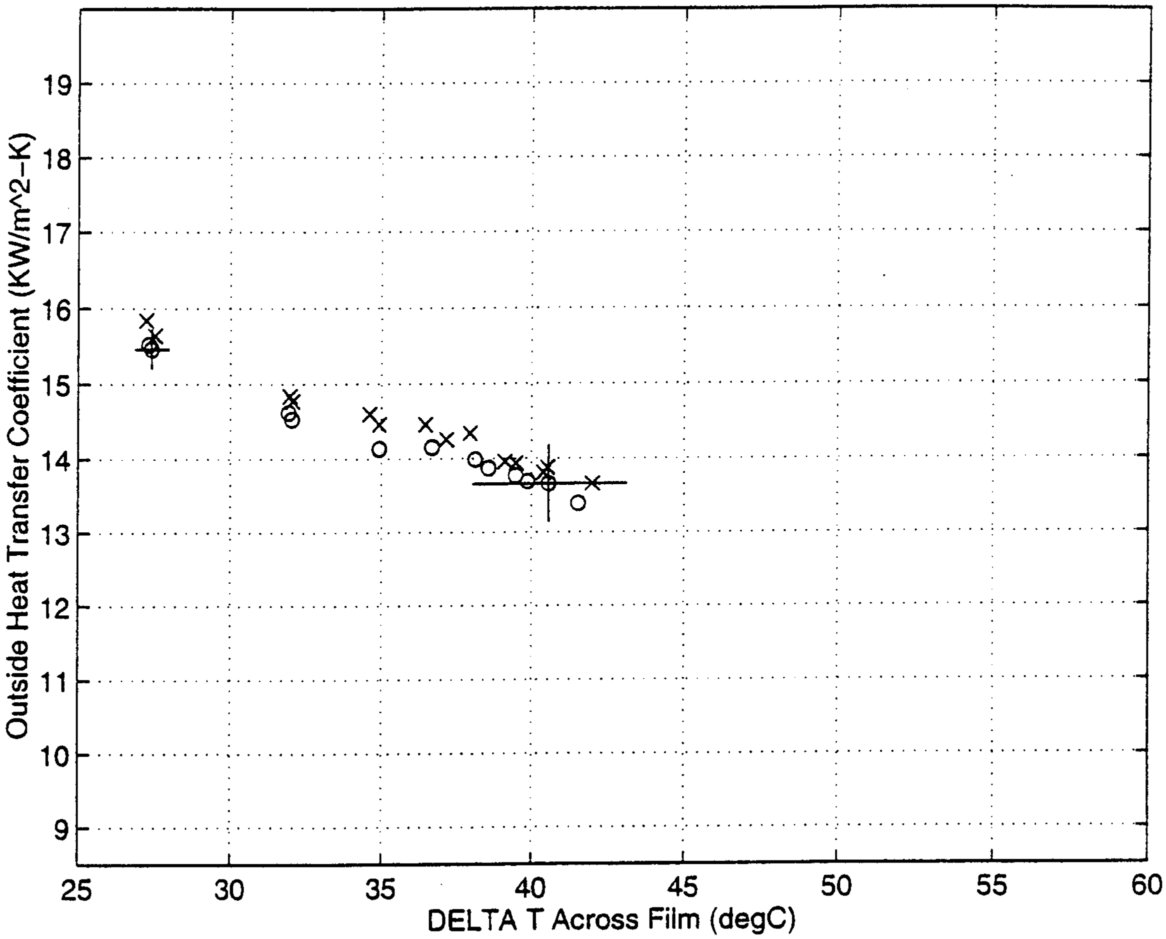

Figure 5.23 Experimentally Determined Values of the Outside Heat Transfer Coefficient vs. Film Temperature Difference for a Stainless Steel Integral-Fin Tube with Fin Height 0.75 mm (Atmospheric)

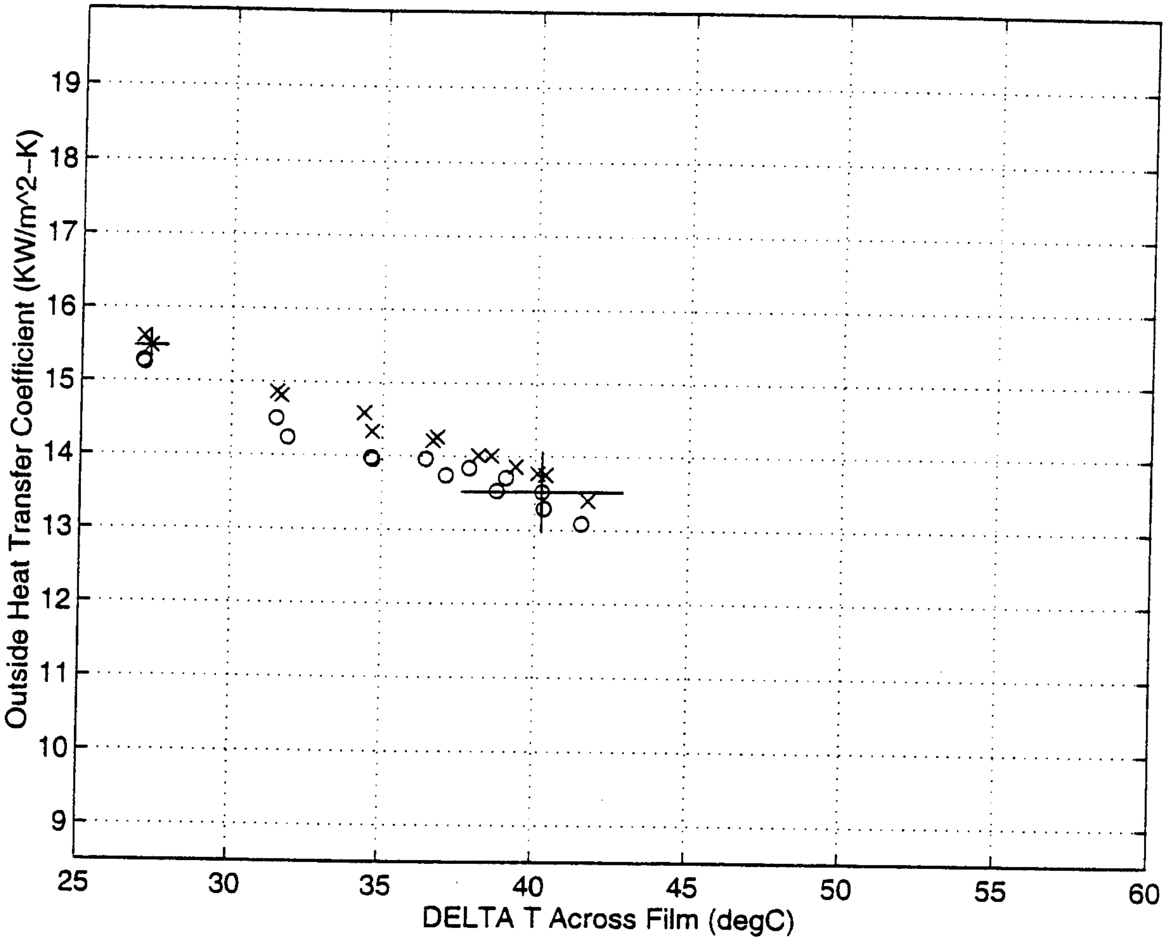

Figure 5.24 Experimentally Determined Values of the Outside Heat Transfer Coefficient vs. Film Temperature Difference for a Stainless Steel Integral-Fin Tube with Fin Height 0.95 mm (Atmospheric)

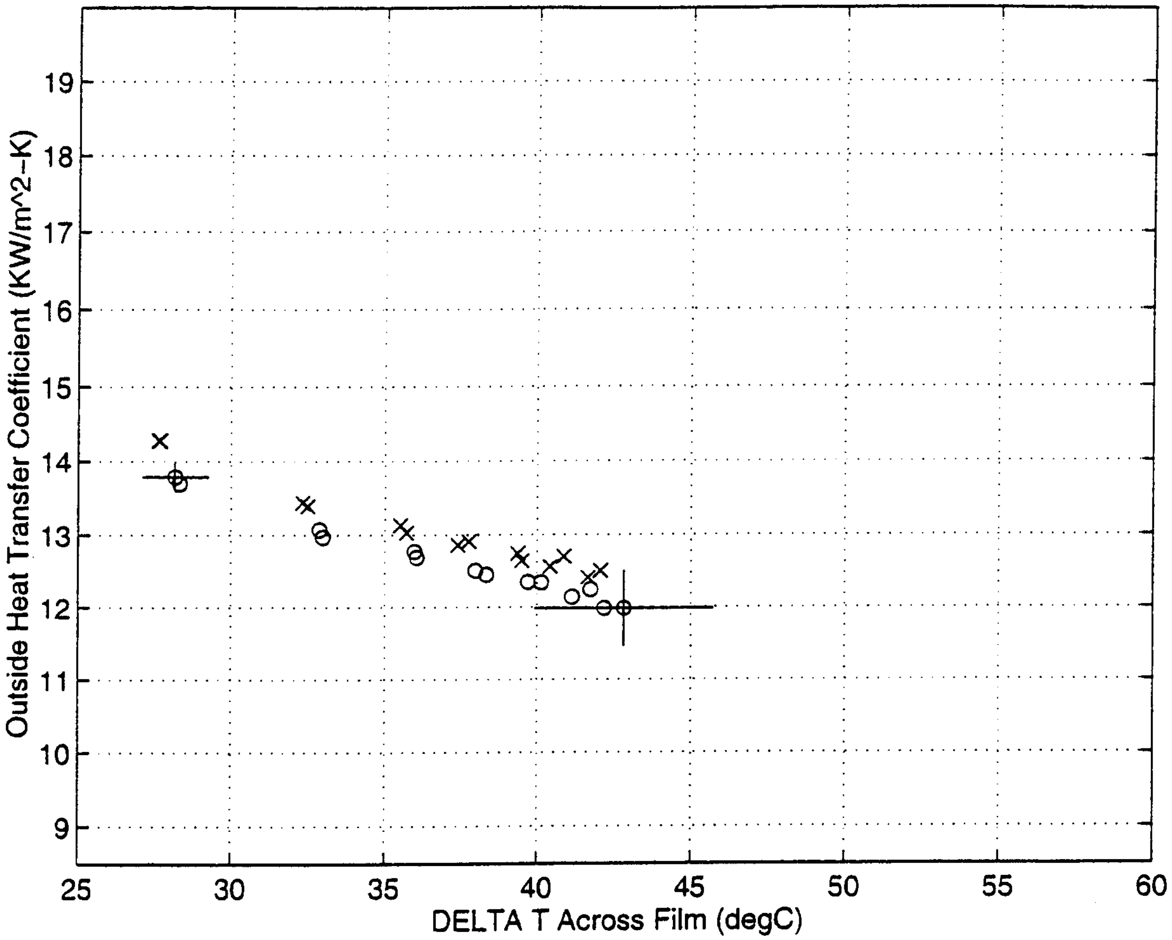

Figure 5.25 Experimentally Determined Values of the Outside Heat Transfer Coefficient vs. Film Temperature Difference for a Stainless Steel Integral-Fin Tube with Fin Height 1.26 mm (Atmospheric)

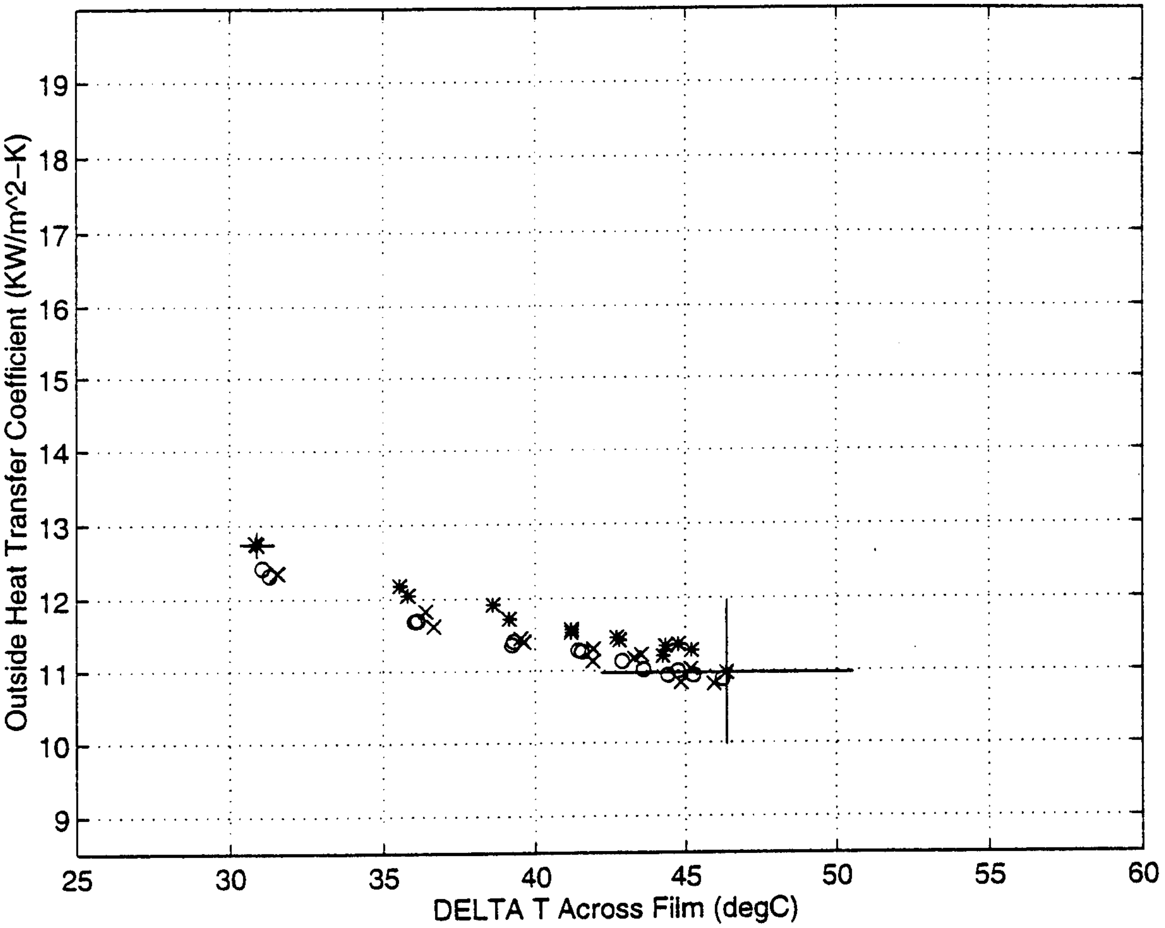

Figure 5.26 Experimentally Determined Values of the Outside Heat Transfer Coefficient vs. Film Temperature Difference for a Stainless Steel Integral-Fin Tube with Fin Height 1.42 mm (Atmospheric)

runs due to the larger heat flux and increased condensation.

Consolidated curve fits of the data are shown in Figures 5.27 and 5.28. For both vacuum and atmospheric runs, as fin height initially increases, the value of h_o increases. For both pressure conditions, the maximum outside heat transfer coefficient is obtained at a fin height near 0.30 mm. As fin height is increased past this optimum, the outside heat transfer coefficient decreases. For fin heights in excess of 0.75 mm under vacuum conditions, heat transfer is actually less than that for a smooth tube. For atmospheric conditions, h_o for fin heights up to 1.5 mm was always more than that for a smooth tube.

4. Comparison of Enhancement ($\epsilon_{\Delta T}$) with Condensate Film Temperature Drop

A plot of enhancement versus fin height, shown in Figure 5.29, showed a trend similar to that observed for the outside heat transfer coefficient. At the optimum fin height of 0.30 mm, the corresponding enhancements are 1.4 and 1.6 for the vacuum and atmospheric conditions. For fin heights less than 0.5 mm and 0.75 mm for vacuum and atmospheric conditions, respectively, the overall enhancement is greater than indicated by the increase in surface area alone. Further increase in fin height yields overall enhancements less than the area enhancement.

Referring to Figure 5.30a, as the fin height is initially increased, the combined effects of additional condensing surface area on the fin flanks and surface tension induced condensate thinning in the interfin region increases heat transfer. When fin height increases beyond the optimum (Figure 5.30b), thinning of the condensate on the increasing fin flank area causes the condensate wedge to rise higher along the lower fin flank and to flood the interfin space. Due to a fin efficiency less than one, less heat is conducted through the fins resulting in less condensation on the fin

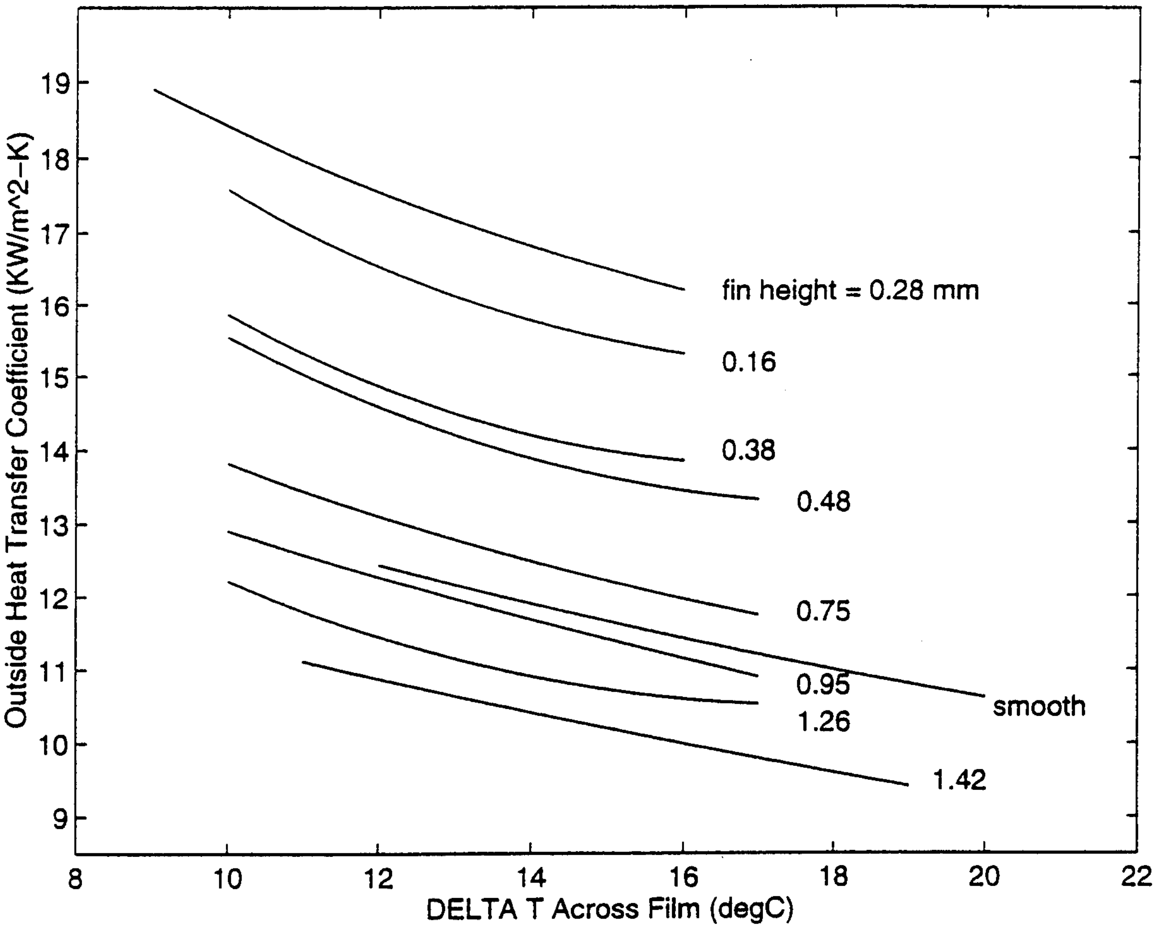

Figure 5.27 Consolidated Curve Fits of Experimentally Determined Values of the Outside Heat Transfer Coefficient vs. Film Temperature Difference for Stainless Steel Integral-Fin Tubes of Various Fin Heights (Vacuum)

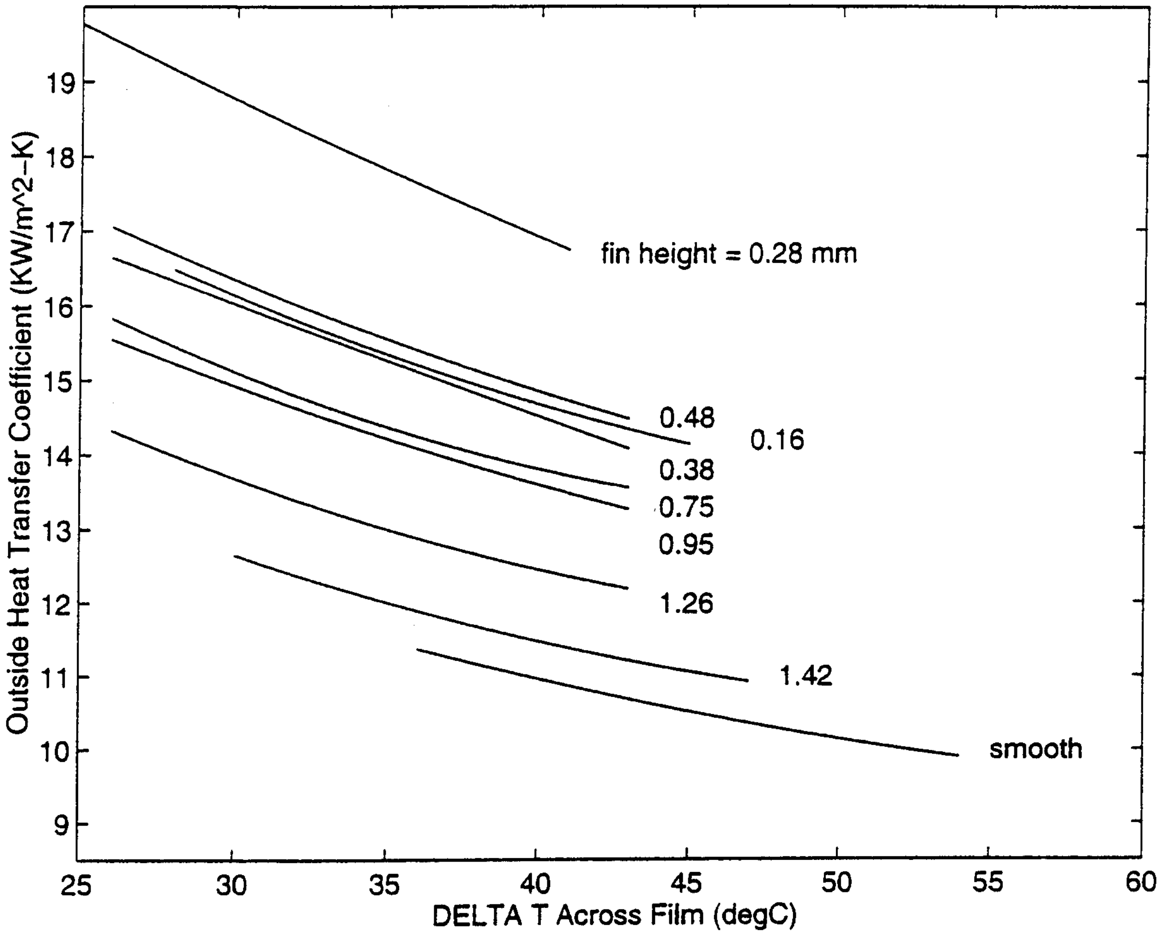

Figure 5.28 Consolidated Curve Fits of Experimentally Determined Values of the Outside Heat Transfer Coefficient vs. Film Temperature Difference for Stainless Steel Integral-Fin Tubes of Various Fin Heights (Atmospheric)

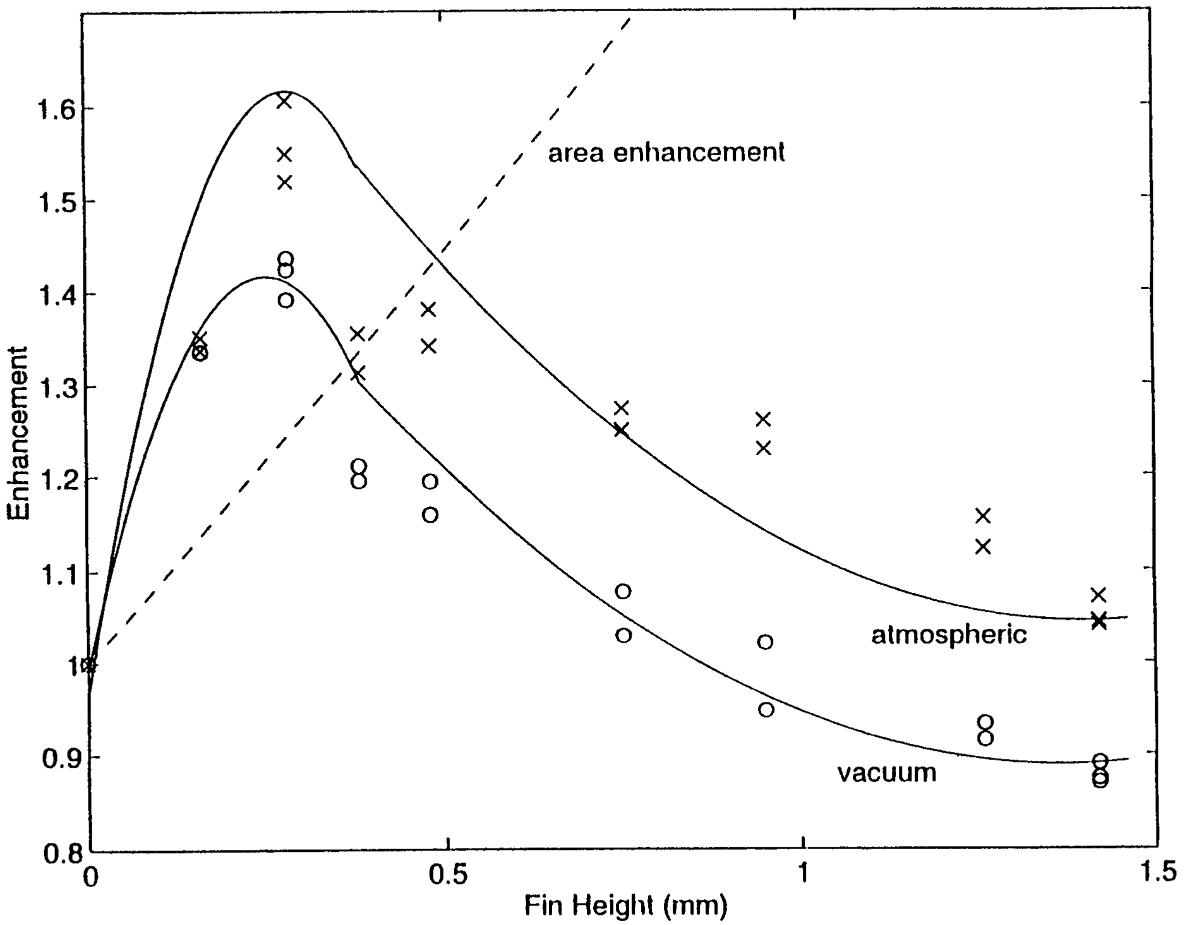

Figure 5.29 Experimentally Determined Values of Enhancement vs. Fin Height for Stainless Steel Integral-Fin Tubes

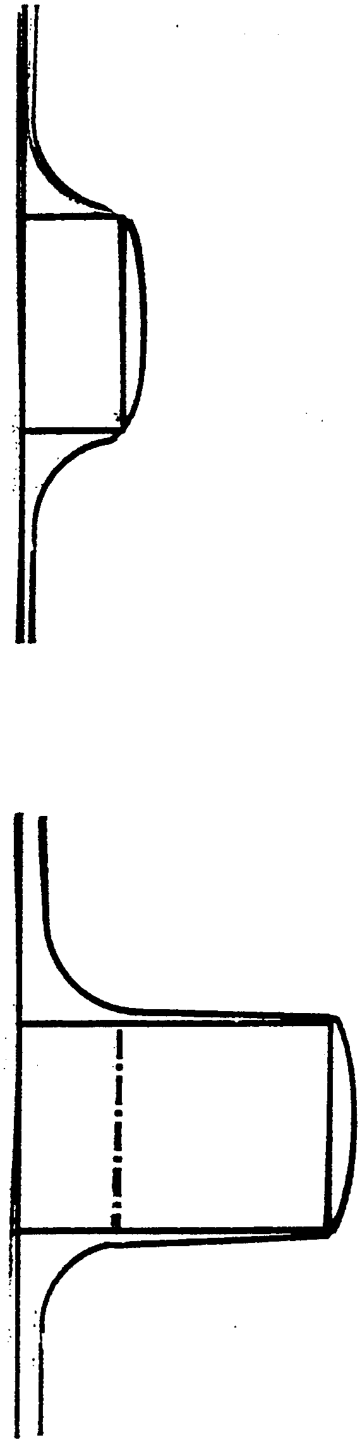

Figure 5.30 Condensation Film Profiles for Short (a) and Long (b) Fins

tips and flank. Increased flooding of the interfin space along the tube circumference due to increasing fin height also causes the flooding angle to decrease as shown previously in Figure 5.4. Thus the enhancing effects of film thinning is more than offset by the deteriorating effects of lower fin conduction and interfin flooding, resulting in a reduction of heat transfer. The decrease in flooding angle as fin height increased could also be observed during experimentation.

5. Comparison of Experimental Enhancement with Predictive Models

Predictive enhancements from the Beatty and Katz [Ref. 17] and the Briggs and Rose [Ref. 28] models were obtained from computer codes written by NPS research associate, Dr. Ashok Das. Tables 5.7 and 5.8 summarize the enhancements from the experimental data and predictive models. These are plotted in Figures 5.31 and 5.32 for comparison.

a. Beatty and Katz

The Beatty and Katz model neglects surface tension and is based on gravity drainage and area enhancement only. The predicted enhancement curves increase until a fin height is reached where the temperature of the fin tip approaches saturation steam temperature. Because surface tension is neglected, the model underpredicts enhancement by up to 10 percent for low fin heights where surface tension induced condensate thinning enhances heat transfer. This relatively small percentage could indicate that although condensate thinning aids in enhancement, the majority of the enhancement is due to the increase in surface area from finning.

For fin heights larger than the experimental optimum, the Beatty and Katz model overpredicted enhancement at an increasing rate because it does not account for the increased flooding from drainage from the fin flanks into the interfin space. For atmospheric test conditions, the overprediction ranges from 16 to 61 percent as fin height is

Fin Height (mm)	Enhancement (Avg Exp)	Enhancement (B & K)	Enhancement (Briggs/Rose)
0.16	1.34	1.29	1.20
0.28	1.42	1.40	1.09
0.38	1.20	1.47	1.02
0.48	1.18	1.52	0.96
0.75	1.05	1.58	0.84
0.95	0.98	1.61	0.86
1.26	0.92	1.63	0.87
1.42	0.88	1.66	0.88

Table 5.7. Experimental and Predicted Values of Enhancement for New Stainless Steel Tubes (Vacuum)

Fin Height (mm)	Enhancement (Avg Exp)	Enhancement (B & K)	Enhancement (Briggs/Rose)
0.16	1.34	1.30	1.27
0.28	1.56	1.41	1.17
0.38	1.33	1.52	1.11
0.48	1.36	1.53	1.01
0.75	1.26	1.61	0.96
0.95	1.24	1.64	0.98
1.26	1.14	1.67	0.99
1.42	1.05	1.69	1.00

Table 5.8. Experimental and Predicted Values of Enhancement for New Stainless Steel Tubes (Atmospheric)

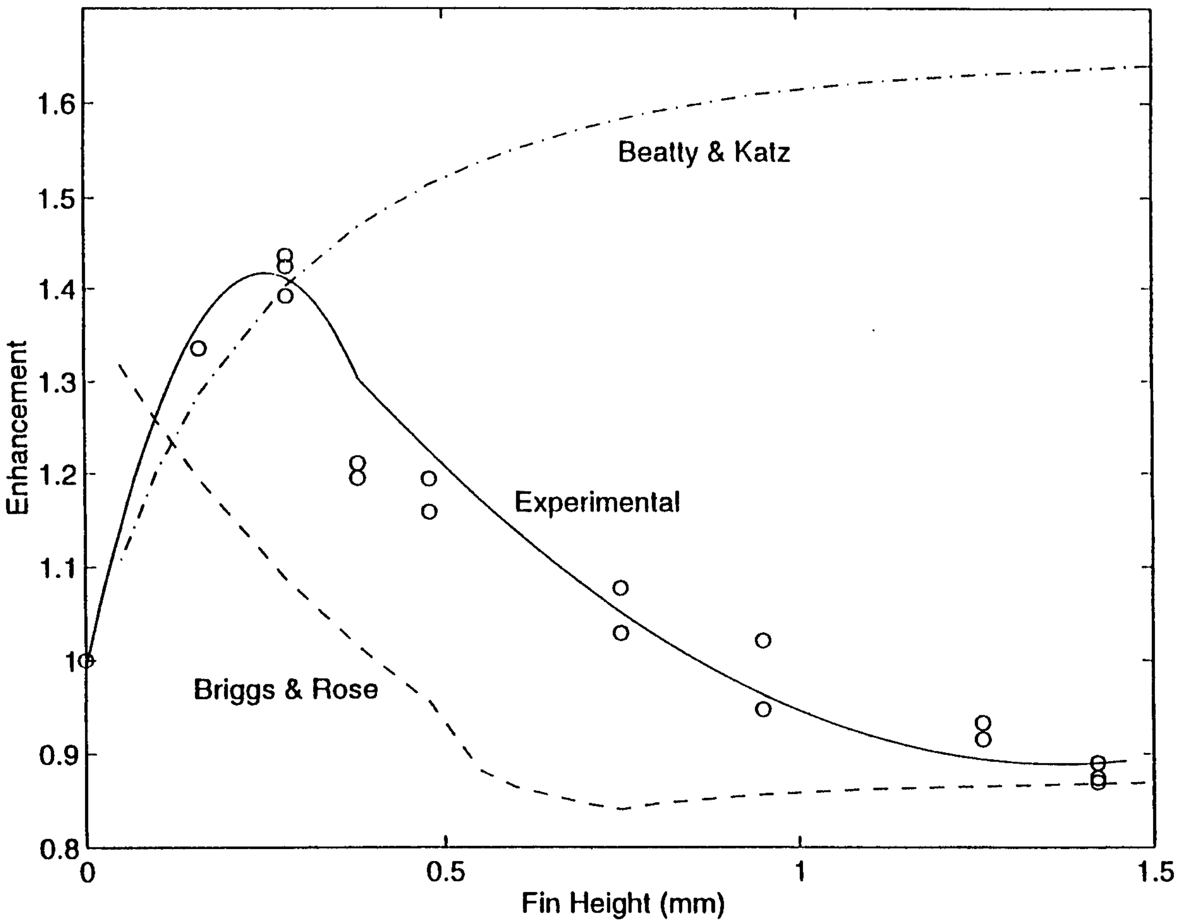

Figure 5.31 Experimental and Predictive Values of Enhancement vs. Fin Height for Integral Fin Stainless Steel Tubes (Vacuum)

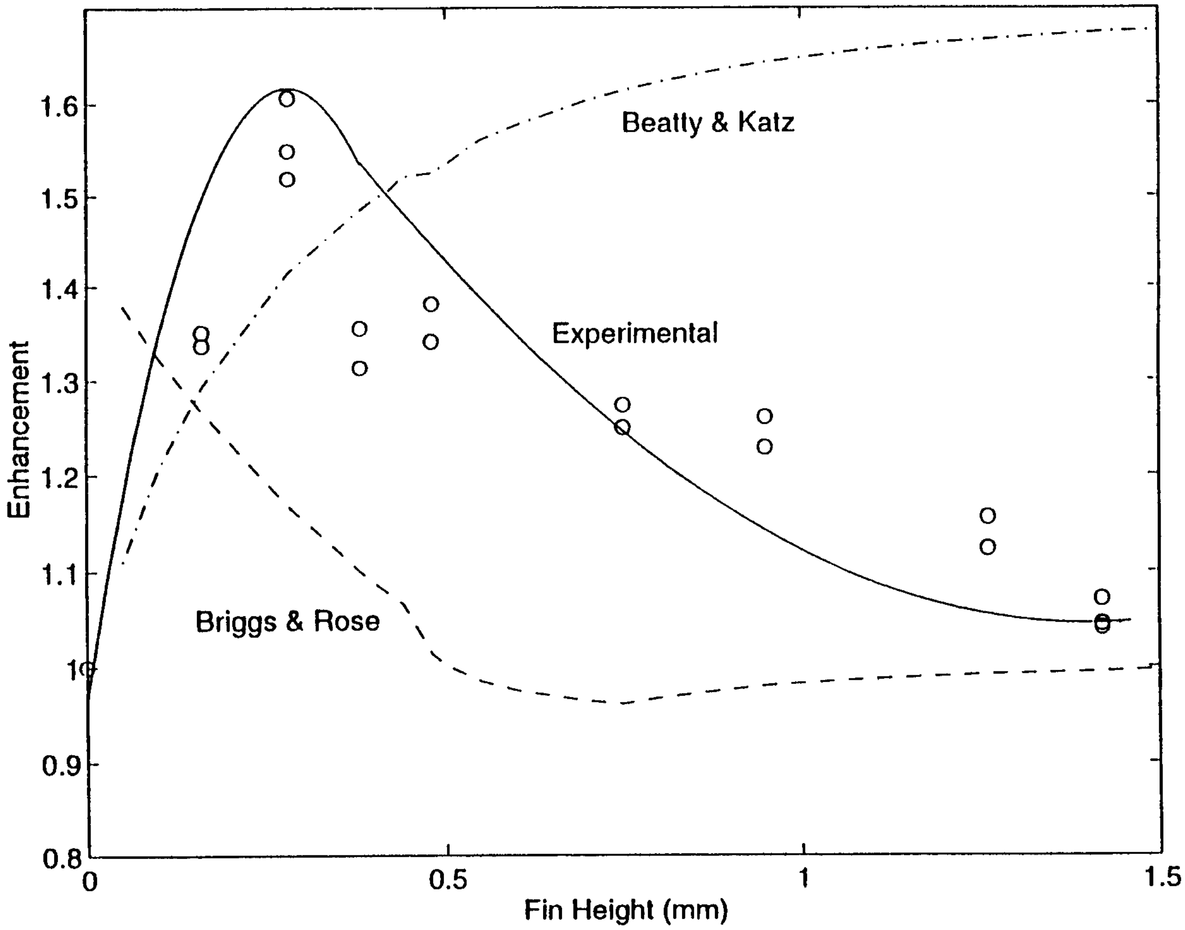

Figure 5.32 Experimental and Predictive Values of Enhancement vs. Fin Height for Integral Fin Stainless Steel Tubes (Atmospheric)

increased from 0.38 mm to 1.42 mm.

The overprediction is greater for vacuum pressure conditions, where film temperatures are smaller, and consequently, surface tension is larger. For this test condition, the Beatty and Katz model overpredicted enhancement from 23 to 89 percent as fin height increased from 0.38 mm to 1.42 mm.

b. Briggs and Rose

The Briggs and Rose predictive model underpredicted enhancement for all fin heights. For vacuum conditions and fin heights greater than 0.48 mm, the model performs very well with predicted values within 20 percent of the experimental enhancements. For atmospheric conditions or fin heights less than 0.48 mm, the model underpredicted enhancement by up to 25 percent. For both pressure conditions, the model follows the experimental trend of the experimental enhancements, however, no optimum is ever reached.

Several reasons could explain the difference in the model's performance at vacuum and atmospheric pressure conditions. First, while the vapor velocity is lower at atmospheric conditions, the effect of the vapor shear may be more pronounced due to the thicker condensate film at atmospheric conditions. Second, the exit of the condensate drops from the bottom of the tube creates an oscillatory motion of the free surface of the condensate retained between the fins. Due to a higher heat flux at atmospheric conditions, the oscillation of the condensate front is much more rapid as compared to vacuum conditions.

For small fin heights, the model is probably invalid. The computer generated values of the average flooding fractions of the interfin space (f_s) and fin flank (f_f) in the unflooded zone were examined for each fin height tested. The average value of f_s remained nearly constant for all fin heights and pressure conditions and was appoximately

80 percent. For both test pressures, f_f increased at an increasing rate from approximately 40 percent at a fin height of 1.42 mm to 100 percent (complete blanking) at a fin height of 0.48 mm. This is due to high heat conduction to the fin tip at small fin heights. The surface tension induced pressure gradient draws the resulting large amount of condensate from the tip to the root. As the liquid wedges rise along the fin due to the volume of condensate, the flanks are eventually blanked. The predicted large increase in enhancement at small fin heights is due to the increased convection from the thin film area at the fin tip. In the limiting case as fin height approaches zero, the constants B_{tip} and B_{int} must approach zero and the sum $[B_1 * (\zeta(\phi_f))^{3/4} + 0.281]$ must approach 0.728. Therefore, the analysis is not valid for such small fin heights.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

Experimental data were obtained for steam condensation on stainless steel smooth and integral-fin tubes at both vacuum and atmospheric conditions. Both Meyer's [Ref. 2] tubes and a new set of tubes were tested. The tube fins had a thickness of 1.0 mm and were spaced 1.5 mm apart. For Meyer's tubes, fin heights ranged from 0.42 to 1.46 mm. For the new set of tubes, fin heights ranged from 0.16 to 1.42 mm. The following conclusions can be drawn:

1. Meyer's experimentally determined enhancements for stainless steel tubes with fin heights between 0.5 and 1.5 mm were confirmed.

2. Increasing fin height has two effects on enhancement. As fin height is initially increased, the increase in surface area and thinning of the condensate film on the upper fin flanks and interfin space increases enhancement. As fin height is increased past an optimum, lower conduction through the fin and increased condensate flooding of the interfin space decreases enhancement. At some point, further increase in fin height actually yields heat transfer performance less than a smooth tube.

3. For the new set of tubes tested, the optimum fin height was approximately 0.30 mm with corresponding enhancements of 1.4 and 1.6 for vacuum and atmospheric pressure conditions respectively.

4. The Briggs and Rose model underpredicted the experimental enhancements for fin heights greater than the optimum. For vacuum conditions, the model performed well with predicted enhancements within 20 percent of experimental values at fin heights greater than the optimum. The model is probably invalid for small fin heights.

5. Flame heating a stainless steel tube is the quickest and easiest method to form an oxide layer that promotes film condensation.

B. RECOMMENDATIONS

1. Test low conductivity tubes of various fin spacings and thicknesses and determine optimum values and the corresponding enhancements.
2. Once optimum fin geometries are determined, explore the commercial fabrication of low conductivity, low fin height condenser tubes.
3. When a large experimental data base is obtained for condensation on low conductivity finned tubes, recalculate the ***B*** constants in the Briggs and Rose predictive model and see if this improves its accuracy.

The following recommendations should improve on the operation and accuracy of the system.

1. Replace the switchboard mounted voltmeter and ammeter with ones accurate within the range 0 to 500 VAC and 0 to 100 amperes AC.
2. Calibrate the apparatus pressure transducer and gage.
3. Recode program DRPALL in QUICK BASIC and install on the Zenith computer system.
4. Modify the uncertainty analysis to provide a more realistic estimate of the experimental uncertainties in enhancement and the inside and outside heat transfer coefficients.

APPENDIX A. OPERATING INSTRUCTIONS

NOTE: If both vacuum and atmospheric data runs are to be taken in the same day, conduct vacuum run first to avoid the delay of cooling down boiler.

A. START-UP

1. Establish the following valve line-up:

Boiler feed	BLR-1	OPEN
Boiler fill and drain	BLR-2	SHUT
Auxiliary condenser cooling water regulator inlet	ACW-1	OPEN
Auxiliary condenser cooling water regulator outlet	ACW-3	SHUT
Condenser pressure gage cut-out		OPEN
Head tank supply	CW-1	SHUT
Head tank overflow	CW-1A	OPEN
Head tank drain	CW-2	SHUT
Cooling water pump vent	CW-3	SHUT
Cooling water pump discharge	CW-4	SHUT
Condenser vacuum line cut-out	VAC-1	SHUT
Accumulator drain	VAC-2	SHUT
Condenser vacuum breaker	VAC-3	SHUT

2. Establish boiler water level at 6 inches above the top of the heater elements.

   a. If water level too high:

      (1) Place boiler fill and drain hose into waste drain.

      (2) Open boiler fill and drain valve BLR-2 and drain to bilge.

      (3) When boiler water level is at proper level, shut boiler fill and drain valve BLR-2.

   b. If water level too low:

CAUTION: DO NOT ADD WATER TO A HOT BOILER. ALLOW BOILER TO COOL BEFORE ADDING WATER.

      (1) Connect boiler fill and drain hose to distilled water tank spigot.

      (2) Open boiler fill and drain valve BLR-2

and gravity fill boiler.

(3) When boiler water level is at proper level, shut boiler fill and drain valve BLR-2.

(4) Disconnect fill and drain hose from distilled water tank spigot.

3. Install the condenser test tube.

NOTE: Each condenser tube has two smooth ends. The longer smooth end is the inlet section.

a. Remove the studs from test condenser inlet in an X-pattern.

b. Remove the flange and nylon component.

c. Remove the previously installed tube.

   (1) Remove the teflon insert and tube assembly by gently twisting the insert while pulling.

   (2) Remove the tube from the teflon insert by twisting.

   (3) Remove the HEATEX insert from the tube by grasping its core with pliers on the outlet side of the tube and gently pulling and twisting.

d. Examine the three small O-rings in the teflon insert and the large O-rings on the nylon and Teflon components for damage and replace if necessary.

e. Pull the petals of the HEATEX insert slightly outward. Install the insert into the tube so that petals fan outward opposite the direction of cooling water flow.

f. Wet the O-rings and tube ends with distilled water to ease installation.

g. Each condenser tube has two smooth ends with one shorter than the other. Insert the shorter smooth end of the test tube into the condenser and through the outlet teflon insert. Seat by gently twisting while pushing.

h. Reinstall the teflon insert, inlet flange assembly, and studs and uniformly snug the fasteners in an X-pattern.

4. Check the test condenser integrity.

    a. Slightly open head tank supply valve CW-1.

    b. Plug in cooling water pump #1.

    c. Slowly open cooling water pump discharge valve CW-4 and adjust to at least 60% rotameter flow. Check for system leaks.

    d. Shut cooling water pump discharge valve CW-4 and unplug cooling water pump.

5. Check auxiliary condenser integrity.

    a. Open auxiliary condenser cooling water regulator outlet valve ACW-3 and adjust to at least 30% rotameter flow.

    b. Check auxiliary condenser cooling system for leaks.

    c. Shut auxiliary condenser cooling water regulator outlet valve ACW-3.

6. Energize the data acquisition unit, computer, CRT, and quartz thermometer power supplies. Verify that the thermocouple and quartz thermometer readings correspond to ambient temperature. Channels on the data acquisition system correspond to the following:

Steam thermocouple (T_{sat})	CH 20
Coolant inlet thermocouple (T_{in})	CH 21
Coolant outlet thermocouple (T_{out})	CH 22
Lab temperature thermocouple (T_{amb})	CH 23
Steam thermocouple (T_{sat})	CH 24
Heater voltage (V)	CH 61
Heater current (I)	CH 62
Pressure transducer (P_{xdcr})	CH 64

B. PROCEEDING FROM A COLD BOILER TO VACUUM OPERATION

1. Energize boiler heater.

   a. Ensure switch 3 circuit breaker is closed in power panel 5 located on the right-hand wall of the hallway to the machine shop.

   b. Ensure power control knob on lab switchboard is turned completely counter-clockwise.

   c. Close heater load bank circuit breaker on left side of lab switchboard.

   d. Place boiler power supply switch located in front of lab switchboard to "ON" position. The switchboard voltmeter reading should drop to zero volts. If voltmeter does not read zero, secure power, and contact lab technician.

   e. Turn power control knob clockwise until switchboard voltmeter reads approximately 40 volts.

2. Warmup and purge system.

   a. When boiler glass becomes warm to the touch, accomplish the following:

      (1) Plug in vacuum pump fan.

      (2) Plug in vacuum pump.

      (3) When gage on vacuum pump accumulator reaches 24 inches Hg, slowly open condenser vacuum line cut-out valve VAC-1.

      (4) As the water begins to boil steadily, the glass piping will quickly warm. This will be indicated by a rapid rise in the CH20 and CH24 thermocouple (T_{sat}) voltages to over 2000 mV. Maintain the purge for at least 10 minutes after the piping has warmed to evacuate air and noncondensibles.

   b. When purge is completed, shut condenser vacuum line cut-out valve VAC-1, and unplug vacuum pump.

   c. After vacuum pump has been unplugged for 5 minutes, unplug vacuum pump fan.

3. Establish system vacuum.

   a. Plug in cooling water pump and fully open discharge valve CW-4 to establish film condensation on test tube.

   b. Fully open auxiliary condenser cooling water regulator outlet valve ACW-3 to quickly cool system and establish operating vacuum.

   c. Adjust panel mounted potentiometer to achieve 1.98 volts on CH61 (198 volts).

   d. As steam temperature and pressure fall, the steam will superheat as it draws heat from the boiler piping. This is indicated by an unfogged sight glass. Allow steam to saturate by waiting until sight glass fogs before continuing.

4. Prepare system for operation.

   a. Load program into HP9826 computer by inserting program disk, typing *LOAD "DRPALL"*, and then pressing EXECUTE key.

   b. Press RUN key.

   c. Type in barometer reading (in Hg) followed by return.

   d. Select *Take Data* option and follow the prompts until the prompt *Enter flowmeter reading* appears.

   e. Start second cooling water pump and adjust discharge valve CW-4 to achieve a 80% rotameter setting.

   f. Shut auxiliary condenser cooling water regulator outlet valve ACW-3 to raise system temperature.

   g. When CH20 thermocouple (T_{sat}) voltage reading approaches 1950 microvolts, slightly open auxiliary condenser cooling water regulator outlet valve ACW-3.

h. Steady state operation is reached when CH61 voltmeter reads 1.978 to 1.982, CH20 thermocouple (T_{sat}) reads 1964 to 1985 microvolts, and CH24 thermocouple (T_{sat}) reads 1961 to 1982 microvolts This corresponds to a heater voltage of 198 volts and a steam temperature of 48.5 to 49.0°C. Operate system at steady state for at least 15 minutes before commencing data runs. Finely adjust auxiliary condenser cooling water regulator valve ACW-3 and potentiometer to maintain saturated steam temperature and system power within limits.

C. PROCEEDING FROM A COLD BOILER TO ATMOSPHERIC OPERATION

1. Fully open head tank supply valve CW-1.

2. Energize boiler heater.

   a. Ensure switch 3 circuit breaker is closed in power panel 5 located on the right-hand wall of the hallway to the machine shop.

   b. Ensure power control knob on lab switchboard is turned completely counter-clockwise.

   c. Close heater load bank circuit breaker on left side of lab switchboard.

   d. Place boiler power supply switch located in front of lab switchboard to "ON" position. The switchboard voltmeter reading should drop to zero volts. If voltmeter does not read zero, secure power, and contact lab technician.

   e. Turn power control knob clockwise until switchboard voltmeter reads approximately 40 volts.

3. Warmup and purge system.

   a. When boiler glass becomes warm to the touch, accomplish the following:

      (1) Plug in vacuum pump fan.

      (2) Plug in vacuum pump.

      (3) When gage on vacuum pump accumulator reaches 24 inches Hg, slowly open condenser vacuum line cut-out valve VAC-1.

      (4) As the water begins to boil steadily, the glass piping will quickly warm. This will be indicated by a rapid rise in the CH20 and CH24 thermocouple (T_{sat}) voltages to over 2000 mV. Maintain the purge for at least 10 minutes after the piping has warmed to evacuate air and noncondensibles.

b. When purge is completed, shut condenser vacuum line cut-out valve VAC-1, and unplug vacuum pump.

c. After vacuum pump has been unplugged for 5 minutes, unplug vacuum pump fan.

4. Prepare system for operation.

CAUTION: DO NOT ALLOW CONDENSER PRESSURE TO EXCEED 15 PSIA.

a. Load program into HP9826 computer by inserting program disk, typing *LOAD "DRPALL"*, and then pressing EXECUTE key.

b. Press RUN key.

c. Type in barometer reading (in Hg) followed by return.

d. Select *Take Data* option and follow the prompts until the prompt *Enter flowmeter reading* appears.

e. Slowly increase boiler voltage until CH61 voltmeter reading reaches 3.85 (385 volts).

f. When CH20 thermocouple (T_{sat}) approaches 3800 microvolts, plug in cooling water pumps and adjust discharge valve CW-4 to achieve a 80% rotameter setting.

g. When CH20 thermocouple (T_{sat}) approaches 4000 microvolts, slightly open auxiliary condenser cooling water regulator outlet valve ACW-3.

h. Steady state operation is reached when CH61 voltmeter reads 3.848 to 3.852, CH20 thermocouple (T_{sat}) reads 4244 to 4290 microvolts, and CH24 thermocouple (T_{sat}) reads 4247 to 4293 microvolts. This corresponds to a heater voltage of 385 volts and a steam temperature of 99.5 to 100.5 °C. Operate system at steady state for at least 15 minutes before commencing data runs. Finely adjust auxiliary condenser cooling water regulator valve ACW-3 and potentiometer to maintain saturated steam temperature and system power within limits.

D. PROCEEDING FROM VACUUM OPERATION TO ATMOSPHERIC OPERATION

1. Fully open head tank supply valve CW-1.
2. Shut cooling water pump discharge valve CW-4.
3. Unplug cooling water pump(s).
4. Shut auxiliary condenser cooling water regulator outlet valve ACW-3.
5. Purge system.
    a. Plug in vacuum pump fan.
    b. Plug in vacuum pump.
    c. When gage on vacuum pump accumulator reaches 24 inches Hg, slowly open condenser vacuum line cut-out valve VAC-1. Maintain the purge for at least 10 minutes to evacuate air and noncondensibles.
    d. When purge is completed, shut condenser vacuum line cut-out valve VAC-1, and unplug vacuum pump.
    e. After vacuum pump has been unplugged for 5 minutes, unplug vacuum pump fan.
6. Prepare system for operation.

CAUTION: DO NOT ALLOW CONDENSER PRESSURE TO EXCEED 15 PSIA.

a. Select *Take Data* option and follow the prompts until the prompt *Enter flowmeter reading* appears.

b. Slowly increase boiler voltage until CH61 voltmeter reading reaches 3.85 (385 volts).

c. When CH20 thermocouple (T_{sat}) approaches 3800 microvolts, plug in cooling water pumps and adjust discharge valve CW-4 to achieve a 80% rotameter setting.

d. When CH20 thermocouple (T_{sat}) approaches 4000 microvolts, slightly open auxiliary condenser cooling water regulator outlet valve ACW-3.

e. Steady state operation is reached when CH61 voltmeter reads 3.848 to 3.852, CH20 thermocouple (T_{sat}) reads 4244 to 4290 microvolts, and CH24 thermocouple (T_{sat}) reads 4247 to 4293 microvolts. This corresponds to a heater voltage of 385 volts and a steam temperature of 99.5 to 100.5 °C. Operate system at steady state for at least 15 minutes before commencing data runs. Finely adjust auxiliary condenser cooling water regulator valve ACW-3 and potentiometer to maintain saturated steam temperature and system power within limits.

E. SECURING SYSTEM

1. Secure boiler heater.
    a. Turn power control knob fully counterclockwise. Voltmeter should indicate zero.
    b. Place boiler power supply switch to "OFF" position.
    c. Open heater load bank circuit breaker.
2. Secure test condenser.
    a. Shut cooling water pump discharge valve CW-4.
    b. Unplug cooling water pump(s).
    c. Shut head tank supply valve CW-1.
3. Secure auxiliary condenser.
    a. Shut auxiliary condenser cooling water regulator inlet valve ACW-1.
    b. Shut auxiliary condenser cooling water regulator outlet valve ACW-3.
4. Turn off quartz thermometer, line printer, and computer power.

APPENDIX B. CALIBRATION AND THERMOPHYSICAL PROPERTY CORRELATIONS

A. ROTAMETER

The Fischer & Porter rotameter (tube model FP-1-35-G-10/83) calibration was accomplished by weighing the quantity of water (W) that flowed through the meter in a prescribed time period (t). The rotameter flow rate (f_r) was varied from ten to seventy percent in five percent increments. Average water temperature for the trial was 21.2°C.

The mass flow rate ($\dot{m}$) for each flow setting was calculated from

$$\dot{m} = \frac{Wg_c}{gt}, \tag{B.1}$$

and the corresponding volumetric flow rate (f_v) was computed from

$$f_v = \frac{Wg_c}{g\rho t}. \tag{B.2}$$

A summary of the raw data and flow rates is contained in Table B.1. A linear regression analysis was used to curve fit the data and obtain the following linear equations

$$\dot{m}\left[\frac{lbm}{s}\right] = (0.029546 + 0.014880 f_r)\frac{\rho}{\rho_{T=70.1°F}}, \tag{B.3}$$

$$f_v\,[gpm] = 0.21275 + 0.10721 f_r, \tag{B.4}$$

$$\dot{m}\left[\frac{kg}{s}\right] = (0.01340 + 0.0067493 f_r)\frac{\rho}{\rho_{T=21.2°C}}, \tag{B.5}$$

and

$$f_v\left[\frac{ltr}{\min}\right] = 0.80527 + 0.40578 f_r. \tag{B.6}$$

Flow (pct)	Weight (lbf)	Time (s)	Flow (kg/s)	Flow (lbm/s)	Flow (ltr/min)	Flow (gpm)
10.0	5.0	28.40	0.080	0.176	4.8	1.27
15.0	10.0	39.18	0.116	0.255	7.0	1.84
20.0	10.0	30.60	0.148	0.327	8.9	2.35
25.0	10.0	24.92	0.182	0.401	10.9	2.89
30.0	10.0	20.96	0.216	0.477	13.0	3.44
35.0	10.0	18.10	0.251	0.552	15.1	3.98
40.0	10.0	15.87	0.286	0.630	17.2	4.54
45.0	10.0	14.44	0.314	0.693	18.9	4.99
50.0	20.0	26.09	0.348	0.767	20.9	5.52
55.0	20.0	23.59	0.385	0.848	23.1	6.11
60.0	20.0	21.60	0.420	0.926	25.2	6.67
65.0	20.0	19.98	0.454	1.00	27.3	7.21
70.0	20.0	18.71	0.485	1.07	29.1	7.70

Table B.1. Rotameter Calibration Data

A comparison of these mass flow rate curves at 20°C with the previously used correlations shows a difference of less than one percent over the range $20 < f_r < 80$.

B. DATA ACQUISITION VOLTMETER

The voltage read by the HP3497A data acquisition system (CH61) was compared to the voltage measured from a test voltmeter. In Chapter III it was noted that the voltage read on CH61 is 1/100 of the actual voltage due to the voltage attenuator placed in the circuit. When the CH61 voltage is multiplied by 100, its value lies within 4.8 percent of the test voltmeter reading. This is within the accuracy of the test meter and the attenuator. The data are shown in Table

B.2. Note that the difference between the test meter and CH61 is approximately 9.5 volts throughout, implying that the test voltmeter, data acquisition system, or both have a constant bias throughout the range of measurement.

Test Voltmeter (V)	CH61 (V x 100)	Difference (pct)
199.8	191	4.4
207.9	198	4.8
229.3	220	4.1
249.3	240	3.7
269.3	260	3.5
289.5	280	3.3
309.6	300	3.1
329.6	320	2.9
399.8	390	2.5

Table B.2. Voltmeter Comparison Data

C. QUARTZ THERMOMETERS AND THERMOCOUPLES

The HP2804A quartz thermometer unit and the copper/constantan thermocouples and their circuit card were tested in a Rosemont fluid bath calibration unit. The quartz thermometer probes were tested in the range of 16° to 25°C corresponding to the expected coolant temperature range of the experimental apparatus. The data are presented in Table B.3. Both probes have a 0.013°C offset compared to the Rosemont test unit so the corrected temperatures are

$$\begin{aligned} T_{in} &= T_1 + 0.013 \\ T_{out} &= T_2 + 0.013 \end{aligned} \qquad \textbf{(B.7)}$$

Test Temp (°C)	Quartz Thermo (04147) (°C)	Quartz Thermo (60459) (°C)
16.36	16.35	16.35
18.58	18.56	18.56
20.57	20.55	20.56
22.32	22.31	22.31
23.08	23.06	23.07
24.36	24.33	24.33
24.86	24.84	24.84

Table B.3. Thermometer Calibration Data

The thermocouples were tested in the ranges of 16° to 25°, 48° to 50°, and 98° to 102°C corresponding to the experimental coolant and steam temperature ranges. These relatively small ranges were selected to give linear fits of thermocouple voltage and temperature. Linear fits within small ranges provide greater precision than a single polynomial fit between large extremes. The test data are presented in Table B.4. The linear equations for the temperature (T) in °C for given thermocouple voltage (Emf) in millivolts are

a. $16° < T < 25°C$

$$\begin{aligned} T_{CH20} &= 0.41666 + 25.0108 Emf \\ T_{CH21} &= 0.44389 + 24.9487 Emf \\ T_{CH22} &= 0.56612 + 24.8415 Emf \\ T_{CH23} &= 0.49260 + 24.8951 Emf \end{aligned} \qquad \textbf{(B.8)}$$

b. $48° < T < 50.25°C$

$$
\begin{aligned}
T_{CH20} &= 2.3045+23.5630Emf \\
T_{CH21} &= 2.2220+23.5630Emf \\
T_{CH22} &= 2.6033+23.3333Emf \\
T_{CH23} &= 2.6267+23.3333Emf
\end{aligned}
\tag{B.9}
$$

c. 98° < T < 101.5°C

$$
\begin{aligned}
T_{CH20} &= 7.3400+21.7645Emf \\
T_{CH21} &= 8.1396+21.5278Emf \\
T_{CH22} &= 7.7550+21.5786Emf \\
T_{CH23} &= 7.8057+21.5900Emf
\end{aligned}
\tag{B.10}
$$

D. PRESSURE TRANSDUCER

The Setra pressure transducer and Heise pressure gage were not calibrated because NPS had no facilities to calibrate vacuum instruments. According to the manufacturer, the transducer measures pressure relative to atmospheric with a zero output at atmospheric, a 5.0 VDC output at 14.7 psi vacuum, and a linear output in between [Ref. 36]. With the apparatus open to the atmosphere, the transducer voltage output reported on CH64 of the data acquisition unit was zeroed. The absolute pressure (P_{xdcr}) as a function of transducer voltage (Emf) is then

$$P_{xdcr} = -2.94Emf+P_{atm} \tag{B.11}$$

where P_{xdcr} is in psia and Emf is in volts.

E. THERMODYNAMIC PROPERTIES

The temperature dependent correlations for saturated steam pressure (P), water viscosity (μ), density (ρ), thermal conductivity (k_w), and latent heat of vaporization (h_{fg}) were obtained from NIST [Ref. 60]. The specific heat of water (C_p) data used in curve fitting were obtained from Incropera [Ref.

Test Temp (°C)	Tcouple CH20 (mV)	Tcouple CH21 (mV)	Tcouple CH22 (mV)	Tcouple CH23 (mV)
16.36	0.638	0.639	0.636	0.638
18.58	0.726	0.726	0.725	0.726
20.57	0.805	0.806	0.805	0.806
22.32	0.876	0.877	0.876	0.877
23.08	0.906	0.907	0.906	0.907
24.36	0.957	0.959	0.958	0.959
24.86	0.978	0.979	0.978	0.979
48.01	1.940	1.943	1.946	1.945
48.85	1.975	1.979	1.982	1.981
49.41	1.999	2.003	2.006	2.005
50.25	2.035	2.038	2.042	2.041
98.44	4.186	4.195	4.203	4.198
99.13	4.217	4.226	4.234	4.230
99.81	4.249	4.258	4.266	4.261
100.48	4.279	4.290	4.297	4.293
101.48	4.327	4.337	4.345	4.340

Table B.4. Thermocouple Calibration Data

3]. The correlations as a function of temperature (T) where T is in °C are

$$P[KPa] = -3.8075649E\text{-}12T^6 + 3.8793438E\text{-}9T^5 + 1.5145197E\text{-}7T^4 + 3.3316902E\text{-}5T^3 + 1.262479E\text{-}3T^2 + 4.6443261E\text{-}2T + 6.0209213E\text{-}1 \quad \textbf{(B.12)}$$

$$\mu\,[kg/m\text{-}s] = 1.078869E\text{-}18T^8 - 5.0954132E\text{-}16T^7 + 1.0329146E\text{-}13T^6 - 1.1878223E\text{-}11T^5 + 8.736755E\text{-}10T^4 - 4.512923E\text{-}8T^3 + 1.8275094E\text{-}6T^2 - 6.3745948E\text{-}5T + 1.80019E\text{-}3 \quad \textbf{(B.13)}$$

$$\rho[kg/m^3] = -8.6244597E\text{-}12T^6+3.9067797E\text{-}9T^5-7.6318631E\text{-}7T^4+8.8129446E\text{-}5T^3-9.0737942E\text{-}3T^2+7.0640968E\text{-}2T+999.81032 \quad \textbf{(B.14)}$$

$$k_w[W/m\text{-}K] = -5.1282051E\text{-}12T^5+1.8735431E\text{-}9T^4-2.3712121E\text{-}7T^3+3.0282634E\text{-}6T^2+1.8883438E\text{-}3T+0.56103333 \quad \textbf{(B.15)}$$

$$h_{fg}[J/kg] = -9.6917486E\text{-}7T^5+2.3213696E\text{-}4T^4-3.0487402E\text{-}2T^3+1.0148364T^2-2370.0473T+2500519.7 \quad \textbf{(B.16)}$$

$$C_p[J/kg\text{-}K] = -4.8411511E\text{-}8T^5+1.529196E\text{-}5T^4-1.8467209E\text{-}3T^3+0.1145064T^2-3.431451T+4216.853 \quad \textbf{(B.17)}$$

APPENDIX C. PROGRAM DRPALL

A. INTRODUCTION

The data acquisition and reduction program DRPALL is written in HP BASIC code. It was used by O'Keefe [Ref. 3], Swenson [Ref. 32], Long [Ref. 34], Cobb [Ref. 6], and Meyer [Ref. 2] to store and process data from experiments conducted on noninstrumented tubes. Although functional, it contained minor arithmetic errors, was inefficient, was poorly commented, and so was completely revised. The logic was restructured to improve efficiency. Processing time was reduced from approximately five minutes to one minute. The same data sets were processed with both versions to assure that the restructure did not affect the results. Liberal addition of comments improved program readability.

The reference for the temperature dependent thermophysical property correlations in Meyer's version of DRPALL was not noted. These were replaced by the latest correlations from NIST [Ref. 60]. Little change in thermophysical properties was noted. A comparison of Meyer's correlations for the saturation pressure, viscosity, density, thermal conductivity, latent heat of vaporization, and specific heat of water with the NIST correlations showed small differences of 0.1, 1.8, 0.05, 0.8, 0.13, and 4.0 percent respectively in the experimental range.

The original computer code calculated the axial fin effeciency incorrectly. From equations (4.14) through (4.17), the M component of efficiency is

$$M = \sqrt{\frac{h_i P}{k_m A}}, \qquad \textbf{(C.1)}$$

the inside fin perimeter is

$$P = \pi D_i, \qquad \textbf{(C.2)}$$

and the fin cross-sectional area is

$$A = \frac{\pi}{4}(D_o^2 - D_i^2)\,. \tag{C.3}$$

In Meyer's version of the code, the fin perimeter is calculated as the sum of the inside and outside perimeters

$$P = \pi(D_i + D_o) \tag{C.4}$$

and the axial fin cross-sectional area is calculated as

$$A = \pi\sqrt{D_o^3 - D_i D_o^2 - D_o D_i^2 + D_i^3}\,. \tag{C.5}$$

These errors were corrected during program revision.

The new code contains options for data acquisition, processing, and printing, merging and copying files, and checking the operation of the electronic sensors. The most recent instrument calibration curve fits from Appendix B were included. The program logic follows the development presented in Chapter IV. Features of the program not previously discussed and the program listing follow.

B. CALCULATION OF MASS FRACTION OF NONCONDENSIBLE GASES

The mass fraction of noncondensible gases (i.e., air) in the apparatus is calculated by comparing the temperature dependent saturation steam pressure with the actual system total pressure. The total mass of gas in the apparatus (m) is equal to the sum of the masses of steam (m_{stm}) and air (m_{air}). In terms of the mass fractions of air and steam,

$$\frac{m_{air}}{m} = 1 - \frac{m_{stm}}{m} \tag{C.6}$$

From thermodynamics, the mass fraction is related to the volume fraction (V_f) and molecular weight (MW) by

$$\frac{m_{stm}}{m} = \frac{V_{f,stm}MW_{stm}}{V_{f,stm}MW_{stm} + V_{f,air}MW_{air}} \tag{C.7}$$

According to Dalton's law of partial pressures

$$p_{air} + p_{stm} = p \tag{C.8}$$

or

$$\frac{p_{air}}{p} = 1 - \frac{p_{stm}}{p} \tag{C.9}$$

and according to the ideal gas law

$$\frac{p_{air}}{p} = V_{f,air} \tag{C.10}$$

and

$$\frac{p_{stm}}{p} = V_{f,stm}. \tag{C.11}$$

Substituting equations (C.2), (C.4), (C.5), and (C.6) into equation (C.1) yields the mass fraction of noncondensibles

$$\frac{m_{air}}{m} = \left[\frac{p_{stm} MW_{stm}}{(p - p_{stm}) MW_{air}} + 1\right]^{-1} \tag{C.12}$$

where p is the total pressure measured by the transducer, p_{stm} is the saturated steam pressure determined from the measured steam temperature, MW_{air} is equal to 28.97, and MW_{stm} is equal 18.016.

While theoretically correct, unrealistic mass fractions were calculated by this method during experimentation. The mass fraction of noncondensibles ranged from -7 to -10 percent during vacuum conditions and 0 to -2 percent for atmospheric conditions. Similar discrepencies were observed by previous researchers [Ref. 42]. The negative readings could have been due to a bias in the pressure transducer or a lack of precision in reading the atmospheric pressure from the mercury barometer. Due to the high density of mercury, it provides a wide range of pressure measurement when used in a barometer but does not yield the precision found in barometers of lower density fluids. Nonlinearity in the pressure transducer could explain the difference in mass fractions observed between vacuum and atmospheric test conditions. Because the transducer pressure is measured relative to atmospheric barometric pressure, any test pressure measurements in this range would yield minimal error. As test pressure diverges from atmospheric, nonlinearity would increase the difference between measured and actual pressure, and yield greater error in mass fraction calculations.

Because neither the pressure gage nor the transducer could be calibrated, the exact cause of the erroneous mass fraction calculations could not be determined. All trials at the same pressure condition produced calculated noncondensible mass fractions in the same range. For each trial, the vacuum pump was operated for at least ten minutes after boiling occurred and before any data was taken. Whatever the precise amount of noncondensible gases in the system, they were assumed small.

C. CORRECTION OF AVERAGE COOLANT VELOCITY FOR HEATEX INSERT

Average coolant velocity (v_w) through the test tube is calculated from the coolant density (ρ), tube inside diameter (D_i), and mass flow ($\dot{m}$) obtained from the rotameter calibration fit in Appendix B where

$$v_w = \frac{4\dot{m}}{\pi \rho D_i^2} . \qquad \textbf{(C.13)}$$

Because the HEATEX insert reduces the cross-sectional area of coolant flow, a correction must be incorporated in equation (C.8). The volume of water held by a tube with an insert installed was compared to the volume of water held by the same tube without an insert. The tube with an insert contained approximately ten percent less volume resulting in a cross-sectional area reduction of 9.18 mm^2. The equation for corrected coolant velocity is then

$$V_w = \frac{\dot{m}}{\rho\left[(\pi D_i^2/4) - 9.18E\text{-}6)\right]}. \tag{C.14}$$

Meyer and previous researchers neglected this correction and consequently underestimated the coolant velocity by about ten percent. Their lower velocity yielded a lower Reynolds number, a lower inside heat transfer coefficient, and shifted the modified Wilson plot to the right. Shifting the modified Wilson plot to the right, reduces its intercept, and yields a falsely higher outside heat transfer leading coefficient.

D. CORRECTION OF HEAT TRANSFER AND LMTD FOR VISCOUS HEATING

At higher coolant flow rates where the temperature rise due to heat transfer is minimum and that due to fluid shear is maximum, viscous heating can account for up to eight percent of the total coolant temperature increase. To improve accuracy, the viscous heating effect must be subtracted from the coolant outlet temperature when calculating the log-mean-temperature difference (*LMTD*) and the overall heat transfer coefficient (U_o) in equations (4.3) and (4.4).

To determine the amount of frictional heating that occurs as a function of coolant velocity, the coolant temperature rise was measured with the quartz thermometers at various flow rates through a 13.1 mm I.D. stainless steel tube with a HEATEX insert installed. Although the temperature difference between the apparatus and the coolant inlet was less than 0.08°C, the test tube was insulated with a rubber sheet and the apparatus was placed under a vacuum to minimize any heat transfer between the apparatus and coolant. The data are presented in Table C.1. A curve fit of the data yielded the following quadratic expression for temperature correction due to viscous heating (T_{cor}) for a given coolant velocity (v_w)

$$T_{cor} = \frac{24.670\,v_w^2 - 6.6468\,v_w - 5.0103}{10^4}, \tag{C.15}$$

where T_{cor} and v_w are in the units of °C and m/s respectively. The correlation is almost identical to the previously used correlation. The correction must be subtracted from the coolant outlet temperature when determining U_o or *LMTD* so that viscous heating will not contribute to the steam to coolant heat transfer calculations.

E. MODIFIED WILSON PLOT ITERATION

The Nusselt correlation for outside heat transfer coefficient is dependent on the outside tube wall temperature (T_{wo}). Because T_{wo}, C_i, and C_o are unknown, an iterative scheme is incorporated into the Modified Wilson plot technique. Arbitrary values of C_i and C_o are initially assumed. For the given value of C_o, an arbitrary value of T_{wo} is assumed for each data point and condensate properties for computing Z in equation (4.35) are calculated from the film temperature (T_f) given by equation (4.30) to compute h_o from equation (4.19). The outside wall temperature is then updated using

$$T_{wo} = T_{stm} - \frac{q''}{h_o}, \tag{C.16}$$

and T_f, Z, and h_o are recalculated with this new value of T_{wo}. The process is repeated until two consecutive values of T_{wo} converge within 0.1 percent.

Once an iteratively determined T_{wo} is found for each data point, a least-squares linear fit of all of the modified

Flowrate (pct)	Velocity (m/s)	Temp Rise (°C)
90	4.696	0.051
85	4.440	0.045
80	4.185	0.040
75	3.930	0.035
70	3.675	0.030
65	3.419	0.026
60	3.164	0.022
55	2.909	0.019
50	2.654	0.015
45	2.398	0.012
40	2.143	0.009
35	1.888	0.007
30	1.633	0.005
25	1.377	0.004
20	1.122	0.002

Table C.1. Viscous Heating Data

Wilson X-Y data points is found. Updated values of C_i and C_o are then determined by taking the reciprocals of the slope and intercept of this linear fit. The old and new values of C_i and C_o are averaged. The entire iterative process for T_{wo}, C_i, and C_o is repeated until the last two values of both C_i and C_o converge within 0.05 percent.

F. CALCULATION OF AVERAGE STEAM VELOCITY

Because average steam velocity (v_∞) is not required when using the Nusselt outside correlation, it is determined for informational purposes only. It is given by

$$V_\infty = \frac{4Q_{in}}{\pi D_{cond}^2 \rho_{stm} h_{fg}} \qquad \textbf{(C.17)}$$

where $Q_{in}/\rho_{stm}h_{fg}$ is the rate of volumetric production of steam and $\pi D^2{}_{cond}/4$ is the cross-sectional area of the test condenser. The net electrical power (Q_{in}) in watts delivered to the apparatus is calculated as

$$Q_{in} = \frac{V^2}{R} - Q_{loss} \qquad \textbf{(C.18)}$$

where V is the system voltage in volts, R is a constant heater resistance of 5.76 ohms, and Q_{loss} is an analytically determined heat loss through the Pyrex piping and insulation.

```
100 ! DRPALL (GEORGE INCHECK)
110 ! MODIFIED:  SEP 1992 (O'KEEFE)
120 ! MODIFIED:  JAN 1993 (LONG)
130 ! MODIFIED:  JUNE 1993 (COBB)
140 ! COMPLETE REVISION JULY 1993 (MEMORY)
150 ! COMPLETE REVISION OCT 1994 (INCHECK)
160 !
170 ! This HP BASIC program is used to collect and process data for steam con-
180 ! densation on finned and smooth tubes as used by COBB, MEYER, and INCHECK.
190 ! Because the unfinned ends of the tubes conduct heat from the condensing
200 ! steam to the internal coolant, they are treated as axial fins in the
210 ! analysis.  Allowance is also made for both vacuum and atmospheric
220 ! condensing conditions.  Disk files are read in the format of both
230 ! INCHECK and MEYER.  A modified Wilson analysis using Nusselt theory is
240 ! used to find the outside convection coefficient as described in Briggs,
250 ! Dale E. and Young, Edwin H.,"Modified Wilson Plot Techniques for
260 ! Obtaining Heat Transfer Correlations for Shell and Tube Heat Exchangers",
270 ! CHEMICAL ENGINEERING PROGRESS, 92, Vol 65.  An iterative technique is used
280 ! to find the inside convection coefficient and is based on the theory of
290 ! Petukhov, B.S., "Heat Transfer and Friction in Turbulent Pipe Flow with
300 ! Variable Physical Properties", ADVANCES IN HEAT TRANSFER, Vol 6, (1970).
310 ! Data and curve-fit equations for calculating the properties of water and
320 ! steam were obtained from NBS/NRC STEAM TABLES (NIST) (1984) and ASME STEAM
330 ! TABLES (1977).  Formulas for converting the raw output of the rotameter,
340 ! thermocouples, and quartz thermometers into SI unit measurements were
350 ! obtained during instrument calibration by INCHECK (Jun 1994).  Thermal
360 ! conductivities of the tube metals were taken from "Thermphysical
370 ! Properties of Matter", TPRC DATA SERIES, Vol 1.
380 !
390 ! Dictionary of variables
400 ! A - Cross-sectional area of tube (m^2).
410 ! Alp - Nusselt coefficient.
420 ! Alp - Outside heat xfer leading coefficient.
430 ! Alpc - Iteratively determined Alp.  Compared to Alp to test for
440 !      convergence.
450 ! Alpsm - Nusselt coefficient for a smooth tube.
460 ! Areacorr - Tube inside x-sectional area loss due to heatex insert (m^2).
470 ! Array - An array for storing T1, T2, Md, Tsteam during Wilson analysis.
480 ! Bamp - System current.
490 ! Bpwr - System power (KW).
500 ! Bvol - System voltage (V).
510 ! Cerr - Absolute error between Ci and Cic.  Used to test convergence.
520 ! Ci - Inside heat transfer leading coefficient.
530 ! Cic - Iteratively determined Ci.  Compared to Ci to test for convergence.
540 ! Cpcw - Specific heat of cooling water (J/kg-K).
550 ! Cpf - Specific heat of condensing film (J/kg-K).
560 ! C1 - Constants in the function FNPvst.
570 ! C2 - Constants in the function FNHfg.
```

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580 ! C3 - Constants in the function FNMuw.
590 ! C4 - Constants in the function FNRhow.
600 ! C5 - Constants in the function FNKw.
610 ! C6 - Constants for function FNTvsv56.
620 ! C7 - Constants for function FNTvsv57.
630 ! C8 - Constants for function FNTvsv58.
640 ! C9 - Constants for function FNrhostm.
650 ! C10 - Constants for function FNTcouple.
660 ! C11 - Constants for function FNTcpw.
670 ! Dcon - Inside diameter of the test condenser (m).
680 ! Ddd - Dummy variable.
690 ! Deltdif - The difference in readings between two temperature sensors.
700 ! Di - Inside diameter of tube (m).
710 ! Droot - Root diameter of finned tube or O.D. of smooth tube (m).
720 ! D_file$ - Read/write data storage file.
730 ! Emf - An array that stores thermocouple voltages.
740 ! Eq - Enhancement ratio for constant heat flux across the condensate film
750 !        for a finned tube vs smooth tube.
760 ! Et - Enhancement ratio for constant temperature drop across the condensate
770 !        film for a finned tube vs smooth tube.
780 ! Etran - Condenser pressure transducer voltage reading (mV).
790 ! Fe1 - Axial fin efficiency for tube inlet length.
800 ! Fe2 - Axial fin efficiency for tube outlet length.
810 ! Fh - Fin height (m).
820 ! Fm - Cooling water flow measured by rotameter (pct).
830 ! Fs - Fin spacing (m).
840 ! Fw - Fin width (m).
850 ! Hfg - Latent heat of vaporization for saturated water evaluated at
860 !       saturation temperature (J/kg).
870 ! Hfgf - Latent heat of condensation for saturated water evaluated at film
880 !       temperature plus the effects of thermal advection (J/kg).
890 ! Hi - Inside heat transfer coefficient (W/m^2-K).
900 ! Ho - Outside heat transfer coefficient (W/m^2-K).
910 ! Hoavg - Average outside heat transfer coefficient (W/m^2-K).
920 ! Ifg - Tube type flag.
930 ! Imc - Tube material flag.
940 ! Iname - Experimenter name flag.
950 ! Iopt - Subroutine option flag.
960 ! Ipc - Experiment pressure flag.  Also indicates the temperature range for
970 !        selecting the proper thermocouple correlations.
980 ! J - Loop counter and array subscript.
990 ! Kcw - Thermal conductivity of cooling water (W/M-K).
1000! Kf - Thermal conductivity of film (W/m-K).
1010! Km - Thermal conductivity of tube metal (W/m-K).
1020! L - Tube condensing length (m).
1030! Lmtd - Log mean temperature difference (degK).
1040! L1 - Tube inlet end length (m).
1050! L2 - Tube outlet end length (m).
```

```
1060! M - The "m" component of fin efficiency (1/m).
1070! Md - Cooling water mass flow rate (kg/s).
1080! Mfng - Molar fraction of non-condensible gases.
1090! Mucw - Viscosity of cooling water (kg/m-s).
1100! Muf - Viscosity of film (kg/m-s).
1110! Mwng - Molar weight of air.
1120! Mwstm - Molar weight of steam.
1130! New - Nusselt function for outside heat transfer on horizontal smooth tube
s.
1140! Nrun - Number of data runs.
1150! Ntercept - Intercept of the modified Wilson plot line.
1160! Ok - User option flag.
1170! Omega - Petukhov's Nusselt number for inside heat transfer.
1180! P - Tube inside perimeter (m).
1190! Patm - Local atmospheric pressure (in Hg).
1200! Pgage - Condenser pressure from gage (KPa).
1210! Ppk1 - Constant K1 in Petukhov's relation.
1220! Ppk2 - Constant K2 in Petukhov's relation.
1230! Pp1 - Numerator in Petukhov's relation Nu=f(Re,Pr).
1240! Pp2 - Denominator in Petukhov's relation Nu=f(Re,Pr).
1250! Prcw - Prandtl Number of cooling water.
1260! Psat - The saturation pressure of steam given saturation temperature (KPa)
.
1270! Pxdcr - Condenser pressure from transducer (KPa).
1280! Q - Heat transfer rate to coolant (J/s).
1290! Qloss - Approximate heat loss in the test apparatus steam piping (W).
1300! Qp - Heat flux to coolant (J/m^2-s).
1310! Qpavg - Average heat flux to coolant (J/m^2-s).
1320! R - Regression coefficient.
1330! Rei - Reynolds Number of cooling water through a circular pipe.
1340! Rhof - Density of film (kg/m^3).
1350! Rhocw - Density of cooling water (kg/m^3).
1360! Rhostm - Density of saturated steam (kg/m^3).
1370! Rm - Wall thermal resistance (K/W).
1380! Slope - Slope of the modified Wilson plot line.
1390! Sse - Used in linear regression analysis.
1400! Sxx - Used in linear regression analysis.
1410! Sxy - Used in linear regression analysis.
1420! Syy - Used in linear regression analysis.
1430! Sumx - Sum of X.
1440! Sumx2 - Sum of X^2.
1450! Sumxy - Sum of X*Y.
1460! Sumy - Sum of Y.
1470! Sumy2 - Sum of Y^2.
1480! Tavg - Average cooling water temperature (degC).
1490! Tcor - Temperature rise of coolant due to viscous heating of internal
1500!        flow (degC).
1510! Temp - Temporary variable.
```

```
1520! Tfilm - Temperature of film (degC).
1530! Tin - Coolant water inlet temperature as measured by thermocouple (degC).
1540! Tout - Coolant water outlet temp as measured by thermocouple (degC).
1550! Trise - Delta T of coolant after subtracting viscous heating effect (degC)
.
1560! Troom - Temperature of laboratory (degC).
1570! Tsteam - Temperature of steam in condenser (degC).
1580! Tsteam1 - Steam temperature measured by Nr1 thermocouple (degC).
1590! Tsteam2 - Steam temperature measured by Nr2 thermocouple (degC).
1600! Two - Tube outside wall temperature (degC).
1610! Twoc - Iteratively obtained wall temp.  Compared to Two for convergence.
1620! Txf - Temperature drop across the condensate film (degC).
1630! Txfavg - Average temperature drop across the condensate film (degC).
1640! T1 - Coolant inlet temperature as measured by qtz thermometer (degC).
1650! T2 - Coolant outlet temperature as measured by qtz thermometer(degC).
1660! Uo - Overall heat transfer coefficient (K/W).
1670! Vapvel - Approximate steam vapor velocity (m/s).
1680! Vcw - Cooling water average velocity (m/s).
1690! Vf - Cooling water volumetric flow (m^3/s).
1700! Vfng - Volume fraction of non-condensible gases.
1710! X - Independent variable in function Y=f(X).  Used for curve fitting by
1720!       least squares method.
1730! Xbar - Mean X.
1740! Xi - Greek "Xi" in Petukhov's equation Nu=f(Re,Pr).
1750! Y - Dependent variable in function Y=f(X).  Used for curve fitting by
1760!       least squares method.
1770! Ybar - Mean Y.
1780!
1790!
1800!
1810  COM /Vst/ C1(6)
1820  COM /Hfg/ C2(5)
1830  COM /Muw/ C3(8)
1840  COM /Rhow/ C4(6)
1850  COM /Kw/ C5(5)
1860  COM /Cc56/ C6(5)
1870  COM /Cc57/ C7(5)
1880  COM /Cc58/ C8(5)
1890  COM /Rhostm/ C9(5)
1900  COM /Tcouple/ C10(3)
1910  COM /Cpw/ C11(5)
1920  COM /Fld/ Iname,Ifg,Di,Droot,Imc,Km,Fs,Fh,Fw,Iopt,Nrun,Patm,Ipc,Bpwr,Vapve
l
1930!
1940! Read function constants.
1950  DATA -0.38075649E-13,0.38793438E-10,0.15146197E-8,0.33316902E-6
1960  DATA 0.1262479E-4,0.46443261E-3,0.60209213E-2
1970  READ C1(*)
```

```
1980  DATA -0.96917486E-9,0.23213696E-6,-0.30487402E-4
1990  DATA 0.10148364E-2,-0.23700473E1,0.25005197E4
2000  READ C2(*)
2010  DATA 0.1078869E-11,-0.50954132E-9,0.10329146E-6,-0.11678223E-4
2020  DATA 0.8736755E-3,-0.4512923E-1,0.18275094E1,-0.63745948E2,0.180019E4
2030  READ C3(*)
2040  DATA -0.88244597E-11,0.39067797E-8,-0.76318631E-6,0.88129446E-4
2050  DATA -0.90737942E-2,0.70640968E-1,0.89981032E3
2060  READ C4(*)
2070  DATA -0.51282051E-8,0.18735431E-5,-0.23712121E-3
2080  DATA 0.30282534E-2,0.18883438E1,0.56103333E3
2090  READ C5(*)
2100  DATA 273.15,2.5878E-2,-5.9853E-7,-3.1242E-11,1.3275E-14,-1.0188E-18
2110  READ C6(*)
2120  DATA 273.15,2.5923E-2,-7.3933E-7,2.8625E-11,1.9717E-15,-2.2486E-19
2130  READ C7(*)
2140  DATA 273.15,2.5931E-2,-7.5232E-7,4.0657E-11,-1.2791E-15,6.4402E-20
2150  READ C8(*)
2160  DATA 0.84464486E-11,.22447156E-8,.13911252E-6,.11268464E-4
2170  DATA .31822098E-3,.49353625E-2
2180  READ C9(*)
2190  DATA 25.661297,-.61954869,.22181644E-1,-.355009E-3
2200  READ C10(*)
2210  DATA -4.8411511E-8,1.529196E-5,-1.8467209E-3,.1145064,-3.431451,4216.853
2220  READ C11(*)
2230  PRINTER IS 1
2240  Patm=30.06 ! in Hg
2250  PRINT USING "4X,""IF TAKING DATA OR OPERATING SENSORS"""
2260  PRINT USING "6X,""ENTER ATMOSPHERIC PRESURE (in Hg)"""
2270  PRINT
2280  INPUT Patm
2290  Patm=Patm/2.041795 !in Hg to psi
2300  !
2310  ! Select desired program option.
2320  BEEP
2330  PRINTER IS 1
2340  PRINT USING "4X,""SELECT OPTION:"""
2350  PRINT USING "6X,""0 EXIT PROGRAM"""
2360  PRINT USING "6X,""1 CHECK REMOTE SENSORS"""
2370  PRINT USING "6X,""2 TAKE DATA"""
2380  PRINT USING "6X,""3 PROCESS DATA"""
2390  PRINT USING "6X,""4 PRINT RAW DATA"""
2400  PRINT USING "6X,""5 MERGE/COPY DATA FILES"""
2410  PRINT
2420  INPUT Iopt
2430  !
2440  ! If exit option selected, go to "END".
2450  IF Iopt=0 THEN GOTO 3180
```

```
2460  !
2470  ! If merge file option selected, call MERGE.
2480  IF Iopt=5 THEN
2490     CALL Merge
2500     GOTO 2320
2510  END IF
2520  !
2530  ! If sensor check option selected, enter appropriate unit temp, read
2540  ! sensors, and display readings on screen.
2550  IF Iopt=1 THEN
2560     BEEP
2570     PRINT USING "4X,""SELECT APPROXIMATE TEMPERATURE RANGE"""
2580     PRINT USING "6X,""0  48 - 50.5 degC"""
2590     PRINT USING "6X,""1  98 - 102  degC"""
2600     PRINT USING "6X,""2  16 - 25   degC"""
2610     PRINT USING "6X,""3  Other"""
2620     INPUT Ipc
2630     CALL Sensor(T1,T2,Tin,Tout,Tsteam1,Tsteam2,Troom,Pxdcr,Bvol,Bamp)
2640     Pxdcr=Pxdcr/6.8947
2650     Tsteam=(Tsteam1+Tsteam2)/2.0
2660     Psat=FNPvst(Tsteam)/6.8947
2670     Bpwr=Bvol^2/5.76E+3
2680     PRINT USING "20X,""SENSOR CHECK"""
2690     PRINT
2700     PRINT USING "2X,""T1     Tin     T2     Tout   Tstm1   Tstm2  Troom"""
2710     PRINT USING "1X,""(degC) (degC) (degC) (degC) (degC)  (degC) (degC)"""
2720     PRINT
2730     PRINT USING "1X,4(DD.DD,2X),2(3D.DD,2X),DD.DD";T1,Tin,T2,Tout,Tsteam1,T
steam2,Troom
2740     PRINT
2750     PRINT USING "1X,""Pxdcr     Psat    Voltage   Power"""
2760     PRINT USING "1X,""(psi)    (psi)     (V)      (KW)"""
2770     PRINT
2780     PRINT USING "1X,2(DD.DD,4X),3D.D,4X,DD.DD";Pxdcr,Psat,Bvol,Bpwr
2790     PRINT
2800     BEEP
2810     PRINT "PRESS 'CONTINUE' TO CONTINUE PROGRAM"
2820     PRINT
2830     PAUSE
2840  ELSE
2850  !
2860  ! For other options, read operator and tube identification data.  Call
2870  ! required subroutine.
2880     BEEP
2890     Iname=0
2900     INPUT "ENTER STUDENT'S NAME (0=INCHECK-Default,1=MEYER)",Iname
2910     IF Iopt=2 OR Iname=1 THEN
2920        BEEP
```

```
2930       PRINT USING "4X,""Select Material Code:"""
2940       PRINT USING "6X,""0 COPPER    1 STAINLESS STEEL"""
2950       PRINT USING "6X,""2 ALUMINUM  3 90:10 CU/NI"""
2960       PRINT USING "6X,""4 TITANIUM """
2970       PRINT
2980       INPUT Imc
2990       BEEP
3000       INPUT "ENTER PRESSURE CONDITION (0=VACUUM,1=ATMOSPHERIC)",Ipc
3010       BEEP
3020       INPUT "ENTER TUBE INSIDE AND ROOT DIAMETERS (mm)",Di,Droot
3030       Di=Di/1000.0
3040       Droot=Droot/1000.0
3050     END IF
3060     IF Iopt=3 OR Iopt=4 THEN
3070       Nrun=14
3080       BEEP
3090       INPUT "ENTER NUMBER OF DATA SETS STORED (DEFAULT=14)",Nrun
3100     END IF
3110     IF Iopt=2 THEN CALL Takedata
3120     IF Iopt=3 THEN CALL Process
3130     IF Iopt=4 THEN CALL Raw
3140   END IF
3150   !
3160   ! Return to main menu.
3170   GOTO 2320
3180   PRINT "HAVE A NICE DAY!!!"
3190   PRINT
3200   END
3210   !
3220   !
3230   !
3240   DEF FNPvst(T)
3250   ! This function takes the saturated temperature [degC] of steam and
3260   ! returns the saturated pressure [KPa].
3270   !
3280   COM /Vst/ C1(6)
3290   P=C1(0)
3300   FOR I=1 TO 6
3310     P=P*T+C1(I)
3320   NEXT I
3330   P=P*1.E+2
3340   RETURN P
3350   FNEND
3360   !
3370   !
3380   !
3390   DEF FNHfg(T)
3400   ! This function takes saturation temp [degC] of water and returns latent
```

```
3410  ! heat of vaporization [J/kg].
3420  !
3430  COM /Hfg/ C2(5)
3440  Hfg=C2(0)
3450  FOR I=1 TO 5
3460     Hfg=Hfg*T+C2(I)
3470  NEXT I
3480  Hfg=Hfg*1.E+3
3490  RETURN Hfg
3500  FNEND
3510  !
3520  !
3530  !
3540  DEF FNMuw(T)
3550  ! This function takes saturation temperature of water [degC] and returns
3560  ! viscosity [kg/m-s].
3570  !
3580  COM /Muw/ C3(8)
3590  Mu=C3(0)
3600  FOR I=1 TO 8
3610     Mu=Mu*T+C3(I)
3620  NEXT I
3630  Mu=Mu*1.E-6
3640  RETURN Mu
3650  FNEND
3660  !
3670  !
3680  !
3690  DEF FNCpw(T)
3700  ! This function takes saturation temp of water [degC] and returns
3710  ! specific heat [J/kg-K].
3720  !
3730  COM /Cpw/ C11(5)
3740  Cp=C11(0)
3750  FOR I=1 TO 5
3760     Cp=Cp*T+C11(I)
3770  NEXT I
3780  RETURN Cp
3790  FNEND
3800  !
3810  !
3820  !
3830  DEF FNRhow(T)
3840  ! This function takes water temp [degC] and returns density [kg/m^3].
3850  !
3860  COM /Rhow/ C4(6)
3870  Ro=C4(0)
3880  FOR I=1 TO 6
```

```
3890     Ro=Ro*T+C4(I)
3900  NEXT I
3910  RETURN Ro
3920  FNEND
3930  !
3940  !
3950  !
3960  DEF FNPrw(T)
3970  ! This function takes water temp [degC] and returns Prandtl Number.
3980  !
3990  Prw=FNCpw(T)*FNMuw(T)/FNKw(T)
4000  RETURN Prw
4010  FNEND
4020  !
4030  !
4040  !
4050  DEF FNKw(T)
4060  ! This function takes water temp [degC] and returns thermal conductivity
4070  ! coefficient [W/m-K].
4080  !
4090  COM /Kw/ C5(5)
4100  Kw=C5(0)
4110  FOR I=1 TO 5
4120     Kw=Kw*T+C5(I)
4130  NEXT I
4140  Kw=Kw*1.E-3
4150  RETURN Kw
4160  FNEND
4170  !
4180  !
4190  !
4200  DEF FNTanh(X)
4210  ! This function computes the hyperbolic tangent of a number.
4220  !
4230  P=EXP(X)
4240  Q=EXP(-X)
4250  Tanh=(P-Q)/(P+Q)
4260  RETURN Tanh
4270  FNEND
4280  !
4290  !
4300  !
4310  DEF FNTvsv56(V)
4320  ! This function takes MEYER thermocouple voltage and returns TSTEAM2 [deg]
.
4330  !
4340  COM /Cc56/ C6(5)
4350  T=C6(0)
```

```
4360  FOR I=1 TO 5
4370     T=T+C6(I)*V^I
4380  NEXT I
4390  T=T-273.15
4400  RETURN T
4410  FNEND
4420  !
4430  !
4440  !
4450  DEF FNTvsv57(V)
4460  ! This function takes MEYER thermocouple voltage and returns TSTEAM1 [degC
].
4470  !
4480  COM /Cc57/ C7(5)
4490  T=C7(0)
4500  FOR I=1 TO 5
4510     T=T+C7(I)*V^I
4520  NEXT I
4530  T=T-273.15
4540  RETURN T
4550  FNEND
4560  !
4570  !
4580  !
4590  DEF FNTvsv58(V)
4600  ! This function takes MEYER thermocouple voltage and returns TROOM [degC].
4610  !
4620  COM /Cc58/ C8(5)
4630  T=C8(0)
4640  FOR I=1 TO 5
4650     T=T+C8(I)*V^I
4660  NEXT I
4670  T=T-273.15
4680  RETURN T
4690  FNEND
4700  !
4710  !
4720  !
4730  DEF FNTfric(Vcw)
4740  ! This function takes coolant velocity [m/s] and returns the increase in
4750  ! water temp [degC] due solely to frictional heating of the internal
4760  ! flow.  This increase was determined by curve fitting the temp rise
4770  ! obtained by circulating coolant at velocities ranging from 1.1 to 4.9
4780  ! m/s through tubes of I.D. 12.14 to 13.37 mm with HEATEX insert.
4790  !
4800  Tcor=2.4669874E-3*Vcw^2-6.6467689E-4*Vcw-5.010371E-4
4810  RETURN Tcor
4820  FNEND
```

```
4830  !
4840  !
4850  !
4860  SUB Heading
4870  ! This subroutine prints headings required for the Takedata, Process, and
4880  ! Raw subroutines.
4890  !
4900  COM /Fld/ Iname,Ifg,Di,Droot,Imc,Km,Fs,Fh,Fw,Iopt,Nrun,Patm,Ipc,Bpwr,Vapve
l
4910  PRINTER IS 701
4920  IF Iname=0 THEN PRINT USING "10X,""Data taken by:                    INCHECK"""
4930  IF Iname=1 THEN PRINT USING "10X,""Data taken by:                    MEYER"""
4940  IF Ifg=0 THEN PRINT USING "10X,""Tube type:                     SMOOTH TUBE"
""
4950  IF Ifg=1 THEN
4960     PRINT USING "10X,""Tube type:                RECTANGULAR FINNED TUBE
"""
4970     PRINT USING "10X,""Fin spacing, width, height: "",DD.DD,2X,Z.DD,2X,Z.DD
,"" (mm)""";Fs,Fw,Fh
4980  END IF
4990  IF Imc=0 THEN PRINT USING "10X,""Tube meterial:                 COPPER"""
5000  IF Imc=1 THEN PRINT USING "10X,""Tube material:                 STAINLESS-ST
EEL"""
5010  IF Imc=2 THEN PRINT USING "10X,""Tube material:                 ALUMINUM"""
5020  IF Imc=3 THEN PRINT USING "10X,""Tube material:                 90/10 CU/NI"
""
5030  IF Imc=4 THEN PRINT USING "10X,""Tube material:                 TITANIUM"""
5040  IF Iopt>2 THEN PRINT USING "10X,""Thermal conductivity:           "",3D.D,""
(W/m-K)""";Km
5050  PRINT USING "10X,""Inside diameter:                  "",DD.DD,"" (mm)""";Di*10
00.
5060  PRINT USING "10X,""Root diameter:                    "",DD.DD,"" (mm)""";Droot
*1000.
5070  IF Ipc=0 THEN PRINT USING "10X,""Pressure condition:          VACUUM"""
5080  IF Ipc=1 THEN PRINT USING "10X,""Pressure condition:          ATMOSPHERIC"
""
5090  IF Iopt=2 THEN
5100     PRINT
5110     PRINT USING "9X,""Inlet     Temp      Steam                 Xducer   Satur
ation"""
5120   PRINT USING "1X,""Flow     Temp      Rise      Temp      Volts      Press
   Press     Mfng"""
5130   PRINT USING "1X,""(pct)  (degC)    (degC)    (degC)      (V)        (psi)
   (psi)    (pct)"""
5140  END IF
5150  IF Iopt=3 THEN
5160     PRINT USING "10X,""System power:                    "",DD.DD,"" (KW)""";Bp
wr
```

```
5170     PRINT USING "10X,""Steam velocity:                        "",D.DD,"" (m/s)""";V
apvel
5180     PRINT USING "10X,""This analysis includes end-fin effect"""
5190     PRINT USING "10X,""HEATEX insert installed in tube"""
5200     IF Ifg=1 THEN
5210       IF Iname=0 THEN
5220         PRINT USING "10X,""Enhancements based on comparison to Incheck sm
ooth tube data"""
5230       ELSE
5240         PRINT USING "10X,""Enhancements based on comparison to Cobb smoot
h tube data"""
5250       END IF
5260     END IF
5270   END IF
5280   IF Iopt=4 THEN
5290     PRINT
5300     PRINT USING "11X,""Room    Inlet  Outlet   Steam    Gage   Xducer"""
5310     PRINT USING "5X,""Flow  Temp    Temp    Temp    Temp    Press   Press
 Volts  Current"""
5320     PRINT USING "4X,""(pct) (degC)  (degC)  (degC)  (degC)   (KPa)   (KPa)
   (V)"""
5330   END IF
5340   PRINT
5350   SUBEND
5360   !
5370   !
5380   !
5390   SUB Sensor(T1,T2,Tin,Tout,Tsteam1,Tsteam2,Troom,Pxdcr,Bvol,Bamp)
5400   ! This subroutine reads the HP2804A quartz thermometer, Setra Model 204
5410   ! pressure transducer, and the unit thermocouple voltages and converts
5420   ! these to usable SI unit measurements.  Readings are taken 5 times over
5430   ! approximately 30 seconds and averaged.
5440   !
5450   COM /Fld/ Iname,Ifg,Di,Droot,Imc,Km,Fs,Fh,Fw,Iopt,Nrun,Patm,Ipc,Bpwr,Vapve
l
5460   DIM Emf(4)
5470   PRINTER IS 1
5480   T1=0.
5490   T2=0.
5500   Emf(0)=0.
5510   Emf(1)=0.
5520   Emf(2)=0.
5530   Emf(3)=0.
5540   Emf(4)=0.
5550   Etran=0.
5560   !
5570   ! Read system voltage and current (V and A).
5580   OUTPUT 709;"AR AF61 AL62 VR5"
```

```
5590  OUTPUT 709;"AS SA"
5600  BEEP
5610  INPUT "CONNECT VOLTAGE LINE",Ok
5620  ENTER 709;Bvol
5630  Bvol=Bvol*100.0
5640  BEEP
5650  INPUT "DISCONNECT VOLTAGE LINE",Ok
5660  OUTPUT 709;"AS SA"
5670  ENTER 709;Bamp
5680  FOR J=1 TO 5
5690  !
5700  ! Read cooling water inlet/outlet temps from quartz thermometers (degC).
5710     OUTPUT 709;"AS SA"
5720     OUTPUT 713;"T1R2E"
5730     WAIT 4
5740     ENTER 713;Temp
5750     T1=T1+Temp
5760     OUTPUT 713;"T2R2E"
5770     WAIT 4
5780     ENTER 713;Temp
5790     T2=T2+Temp
5800     OUTPUT 713;"T3R2E"
5810  !
5820  ! Read pressure transducer.
5830     OUTPUT 709;"AR AF64 AL64 VR5"
5840     OUTPUT 709;"AS SA"
5850     ENTER 709;Temp
5860     Etran=Etran+Temp
5870  !
5880  ! Read steam, cooling water, and room temp thermocouple voltages (mV).
5890     OUTPUT 709;"AR AF20 AL24 VR5"
5900     FOR I=0 TO 4
5910        OUTPUT 709;"AS SA"
5920        ENTER 709;Temp
5930        Emf(I)=Emf(I)+Temp*1.E+3
5940     NEXT I
5950  NEXT J
5960  !
5970  ! Average voltages and convert to SI units.
5980  T1=T1/5.0+.013
5990  T2=T2/5.0+.013
6000  Etran=Etran/5.0
6010  Pxdcr=(-2.94*Etran+Patm)*6.89473  ! psi to KPa
6020  Emf(0)=ABS(Emf(0))/5.0
6030  Emf(1)=ABS(Emf(1))/5.0
6040  Emf(2)=ABS(Emf(2))/5.0
6050  Emf(3)=ABS(Emf(3))/5.0
6060  Emf(4)=ABS(Emf(4))/5.0
```

```
6070  IF Ipc=0 THEN      !Approx 50 degC range
6080     Tsteam1=2.222+(23.563*Emf(0))
6090     Tsteam2=2.6287+(23.3333*Emf(4))
6100  END IF
6110  IF Ipc=1 THEN      !Approx 100 degC range
6120     Tsteam1=8.1396+(21.5278*Emf(0))
6130     Tsteam2=7.8057+(21.59*Emf(4))
6140  END IF
6150  IF Ipc=2 THEN      !Ambient temperature
6160     Tsteam1=.44389+(24.9487*Emf(0))
6170     Tsteam2=.4926+(24.8951*Emf(4))
6180  END IF
6190  IF Ipc=3 THEN      !All other temp ranges
6200     Tsteam1=FNTcouple(Emf(0))
6210     Tsteam2=FNTcouple(Emf(4))
6220  END IF
6230  Deltdif=Tsteam1-Tsteam2
6240  IF ABS(Deltdif)>.1 THEN
6250     PRINT USING "4X,""STEAMSIDE TCOUPLES DIFFER BY "",DD.D,"" degC""";Deltd
if
6260     PRINT
6270  END IF
6280  Tin=.56612+(24.8415*Emf(1))
6290  Tout=.41666+(25.0108*Emf(2))
6300  Deltdif=Tout-Tin-T2+T1
6310  IF ABS(Deltdif)>.05 THEN
6320     PRINT USING "4X,""QUARTZ THERMO AND TCOUPLE DELTA-T DIFFERS BY "",DD.DD
,"" degC""";Deltdif
6330     PRINT
6340  END IF
6350  Troom=FNTcouple(Emf(3))
6360  SUBEND
6370  !
6380  !
6390  !
6400  SUB Raw
6410  ! This subroutine prints the raw data obtained from INCHECK or MEYER
6420  ! experimentation.
6430  !
6440  COM /Fld/ Iname,Ifg,Di,Droot,Imc,Wm,Fs,Fh,Fw,Iopt,Nrun,Patm,Ipc,Bpwr,Vapve
l
6450  DIM Emf(20)
6460  BEEP
6470  INPUT "GIVE THE NAME OF THE RAW DATA FILE",D_file$
6480  ASSIGN @File TO D_file$
6490  PRINTER IS 701
6500  PRINT USING "10X,""Program Name:                DRPALL"""
6510  PRINT USING "10X,""Raw data stored on file:      "",10A";D_file$
```

```
6520  IF Iname=0 THEN
6530     ENTER @File;Ifg,Imc,Ipc
6540     ENTER @File;Fs,Fw,Fh
6550     ENTER @File;Di,Droot
6560  ELSE
6570     ENTER @File;Ifg,Ddd
6580     ENTER @File;Ddd,Fs,Fw,Fh
6590  END IF
6600  IF Imc=0 THEN Km=390.8
6610  IF Imc=1 THEN Km=14.3
6620  IF Imc=2 THEN Km=231.8
6630  IF Imc=3 THEN Km=55.3
6640  IF Imc=4 THEN Km=18.9
6650  CALL Heading
6660  FOR J=1 TO Nrun
6670     IF Iname=0 THEN
6680        ENTER @File;Fm,T1,T2,Tsteam,Pgage,Pxdcr,Troom,Bvol,Bamp
6690     ELSE
6700        ENTER @File;Bvol,Bamp,Ddd,Fm,T1,T2,Pgage,Pxdcr,Emf(*)
6710        Tsteam1=FNTvsv57(Emf(0))
6720        Tsteam2=FNTvsv56(Emf(1))
6730        Troom=FNTvsv58(Emf(2))
6740        Pgage=Pgage/1000.0
6750        Pxdcr=Pxdcr/1000.0
6760        Tsteam=Tsteam1
6770        Bvol=Bvol*100.0
6780     END IF
6790  P1=Pgage
6800  P2=Pxdcr
6810 PRINT USING "1X,2(DD,3X),3(DD.DD,3X),4(3D.D,3X),D.DD";J,Fm,Troom,T1,T2,Tste
am,P1,P2,Bvol,Bamp
6820  NEXT J
6830  ASSIGN @File TO *
6840  SUBEND
6850  !
6860  !
6870  !
6880  SUB Takedata
6890  ! This subroutine records data obtained from the experimental apparatus.
6900  !
6910  COM /Fld/ Iname,Ifg,Di,Droot,Imc,Km,Fs,Fh,Fw,Iopt,Nrun,Patm,Ipc,Bpwr,Vapve
l
6920  INPUT "GIVE A NAME FOR THE RAW DATA FILE",D_file$
6930  CREATE BDAT D_file$,30
6940  ASSIGN @File TO D_file$
6950  PRINTER IS 701
6960  PRINT USING "10X,""Program Name:                    DRPALL"""""
6970  PRINT USING "10X,""Raw data stored om file:         "",10A";D_file$
```

```
6980  !
6990  ! Read tube geometry and experimental conditions.
7000  BEEP
7010  INPUT "ENTER GEOMETRY CODE (0=SMOOTH,1=RECTANGULAR FIN)",Ifg
7020  Fh=0.
7030  Fs=0.
7040  Fw=0.
7050  IF Ifg=1 THEN
7060     BEEP
7070     INPUT "ENTER FIN SPACING, HEIGHT, AND WIDTH (mm)",Fs,Fh,Fw
7080  END IF
7090  ! Write fin geometry, tube material, and pressure condition to the data fi
le.
7100  OUTPUT @File;Ifg,Imc,Ipc
7110  OUTPUT @File;Fs,Fw,Fh
7120  OUTPUT @File;Di,Droot
7130  CALL Heading
7140  !
7150  ! Take experimental data thru subroutine SENSOR.  By using the molar
7160  ! weights of steam and air, determine the molar fraction of noncondensible
7170  ! gases in the system.  If the data set is acceptable, write it to the
7180  ! data file.  Repeat until all data is recorded.
7190  Mwstm=18.016
7200  Mwng=28.97
7210  J=1
7220  BEEP
7230  INPUT "ENTER FLOWMETER READING",Fm
7240  IF Fm<20. OR Fm>85. THEN
7250     BEEP
7260     PRINTER IS 1
7270     PRINT "INCORRECT FLOWMETER READING--REENTER"
7280     PRINT
7290     GOTO 7220
7300  END IF
7310  CALL Sensor(T1,T2,Tin,Tout,Tsteam1,Tsteam2,Troom,Pxdcr,Bvol,Samp)
7320  BEEP
7330  INPUT "ENTER PRESSURE GAGE READING (psi)",Pgage
7340  Pgage=Pgage*6.8947
7350  Tsteam=(Tsteam1+Tsteam2)/2.0
7360  Psat=FNPvst(Tsteam)
7370  Vfng=(Pxdcr-Psat)/Pxdcr
7380  Mfng=1./((1./Vfng-1.)*Mwstm/Mwng+1.)
7390  Mfng=Mfng*100.
7400  PRINTER IS 701
7410 PRINT USING "2X,DD,4X,6(3D.DD,4X),4D.D";Fm,T1,T2-T1,Tsteam,Bvol,Pxdcr/6.894
7,Psat/6.8947,Mfng
7420  BEEP
7430  INPUT "OK TO ACCEPT THIS DATA SET (1=Y,0=N)?",Ok
```

```
7440  IF Ok=1 THEN
7450     OUTPUT @File;Fm,T1,T2,Tsteam,Pgage,Pxdcr,Troom,Bvol,Bamp
7460     PRINTER IS 701
7470     PRINT
7480     BEEP
7490     INPUT "WILL THERE BE ANOTHER DATA RUN (0=YES,1=NO)?",Ok
7500     IF Ok=0 THEN
7510        J=J+1
7520        GOTO 7220
7530     ELSE
7540        Nrun=J
7550     END IF
7560  ELSE
7570     PRINTER IS 1
7580     PRINT "THE PREVIOUS DATA SET WAS DISCARDED!!"
7590     GOTO 7220
7600  END IF
7610  ASSIGN @File TO *
7620  PRINTER IS 701
7630  PRINT
7640  PRINT Nrun,"DATA SETS WERE WRITTEN TO THE FILE"
7650  SUBEND
7660  !
7670  !
7680  !
7690  SUB Process
7700  ! This subroutine processes MEYER or INCHECK data files using the modified
7710  ! Wilson method.  Values of the leading coefficients for the inside and
7720  ! outside heat transfer correlations are found using Petukhov and Nusselt
7730  ! theory respectively.  Coolant velocity, heat transfer coefficients, heat
7740  ! flux, and temperature drop across the condensing film are printed for
7750  ! each data point.  Curve fit data for the overall heat transfer
7760  ! coefficient vs heat flux and film delta-T are printed.
7770  !
7780  COM /Fld/ Iname,Ifg,Di,Droot,Imc,Km,Fs,Fh,Fw,Iopt,Nrun,Patm,Ipc,Bpwr,Vapve
l
7790  DIM Array(27,6),Emf(20)
7800  BEEP
7810  INPUT "GIVE THE NAME OF THE EXISTING DATA FILE",D_file$
7820  ASSIGN @File TO D_file$
7830  PRINTER IS 701
7840  PRINT USING "10X,""Program Name:                    DRPALL"""
7850  PRINT USING "10X,""Raw data stored on file:         "",10A";D_file$
7860  IF Iname=0 THEN
7870     ENTER @File;Ifg,Imc,Ipc
7880     ENTER @File;Fs,Fw,Fh
7890     ENTER @File;Di,Droot
7900  ELSE
```

```
7910      ENTER @File;Ifg,Ddd
7920      ENTER @File;Ddd,Fs,Fw,Ddd
7930      BEEP
7940      INPUT "ENTER FIN HEIGHT (mm)",Fh
7950   END IF
7960   !
7970   ! Initialize tube geometry and thermal conductivity.
7980   L=.13335
7990   L1=.060325
8000   L2=.034925
8010   Dcon=.1524
8020   Areacorr=9.18214E-6
8030   IF Imc=0 THEN Km=390.8
8040   IF Imc=1 THEN Km=14.3
8050   IF Imc=2 THEN Km=231.8
8060   IF Imc=3 THEN Km=55.3
8070   IF Imc=4 THEN Km=18.9
8080   Ci=2.5
8090   IF Iname=0 THEN
8100      IF Ipc=0 THEN Alpsm=.815
8110      IF Ipc=1 THEN Alpsm=.827
8120   ELSE
8130      IF Ipc=0 THEN Alpsm=.81
8140      IF Ipc=1 THEN Alpsm=.85
8150   END IF
8160   Alp=2.6
8170   Rm=LOG(Droot/Di)/(2.0*PI*L*Km)
8180   P=PI*Di
8190   A=(Droot^2-Di^2)*PI/4.0
8200   Voltavg=0.
8210   Tstmavg=0.
8220   IF Ipc=0 THEN Qloss=125.
8230   IF Ipc=1 THEN Qloss=348.
8240   !
8250   ! Read file and compute necessary values for Wilson iteration.  Store
8260   ! these values in Array for iterative processing.
8270   FOR J=1 TO Nrun
8280      IF Iname=0 THEN
8290         ENTER @File;Fm,T1,T2,Tsteam,Ddd,Ddd,Ddd,Bvol,Ddd
8300      ELSE
8310         ENTER @File;Bvol,Ddd,Ddd,Fm,T1,T2,Ddd,Ddd,Emf(*)
8320         Bvol=Bvol*100.
8330         Tsteam=FNTvsv57(Emf(0))
8340      END IF
8350      Voltavg=Voltavg+Bvol
8360      Tstmavg=Tstmavg+Tsteam
8370   !
8380   ! Calculate the properties of the cooling water at its avg temperature.
```

```
8390  ! Based on these properties, calculate Omega by Petukhov theory.
8400      Md=(.6763*Fm+1.34212)*FNRhow(T1)/1.E+6
8410      Tavg=(T1+T2)/2.0
8420      Cpcw=FNCpw(Tavg)
8430      Rhocw=FNRhow(Tavg)
8440      Kcw=FNKw(Tavg)
8450      Mucw=FNMuw(Tavg)
8460      Prcw=FNPrw(Tavg)
8470      Vf=Md/Rhocw
8480      Vcw=4.0*Vf/(PI*Di^2-Areacorr)
8490      Rei=Rhocw*Vcw*Di/Mucw
8500      Xi=(1.82*LGT(Rei)-1.64)^(-2)
8510      Ppk1=1.0+3.4*Xi
8520      Ppk2=11.7+1.8*Prcw^(-1.0/3.0)
8530      Pp1=(Xi/8.0)*Rei*Prcw
8540      Pp2=Ppk1+Ppk2*(Xi/8.0)^,5*(Prcw^.6667-1.0)
8550      Omega=Pp1/Pp2
8560  !
8570  ! Calculate the log-mean-temp-difference after correcting for the
8580  ! frictional effects of heating.  Then calculate the heat flux and
8590  ! overall heat transfer coefficient.
8600      Tcor=FNTfric(Vcw)
8610      Trise=T2-T1-Tcor
8620      Lmtd=Trise/LOG((Tsteam-T1)/(Tsteam-T2+Tcor))
8630      Q=Md*Cpcw*Trise
8640      Qp=Q/(PI*Droot*L)
8650      Uo=Qp/Lmtd
8660  !
8670  ! Store the necessary values for Wilson iteration.
8680      Array(J-1,0)=Tsteam
8690      Array(J-1,1)=Kcw
8700      Array(J-1,2)=Qp
8710      Array(J-1,3)=Uo
8720      Array(J-1,4)=Omega
8730      Array(J-1,5)=Vcw
8740      Array(J-1,6)=Lmtd
8750  NEXT J
8760  ASSIGN @File TO *
8770  !
8780  ! Calculate the power and steam vapor velocity.  Print page heading.
8790  Voltavg=Voltavg/Nrun
8800  Tstmavg=Tstmavg/Nrun
8810  Bpwr=Voltavg^2/5.76
8820  Hfg=FNHfg(Tstmavg)
8830  Rhostm=FNRhostm(Tstmavg)
8840  Vapvel=4*(Bpwr-Qloss)/(PI*Rhostm*Hfg*Dcon^2)
8850  Bpwr=Bpwr/1.E+3
8860  CALL Heading
```

```
8870  !
8880  ! Iterate for Ci and Alp until they converge within 0.05% of Cic and Alpc.
8890  BEEP
8900  Sumx=0.
8910  Sumy=0.
8920  Sumx2=0.
8930  Sumy2=0.
8940  Sumxy=0.
8950  FOR J=1 TO Nrun
8960     Tsteam=Array(J-1,0)
8970     Kcw=Array(J-1,1)
8980     Qp=Array(J-1,2)
8990     Uo=Array(J-1,3)
9000     Omega=Array(J-1,4)
9010  !
9020  ! Solve for Two by iteration and then find Hi.
9030     Two=Tsteam-5.0
9040     Tfilm=(Tsteam+2.0*Two)/3.0
9050     Rhof=FNRhow(Tfilm)
9060     Kf=FNKw(Tfilm)
9070     Muf=FNMuw(Tfilm)
9080     Hfgf=FNHfg(Tfilm)+.68*FNCpw(Tfilm)*(Tsteam-Two)
9090     New=(Kf^3*9.81*Hfgf*Rhof^2/(Muf*Droot*(Tsteam-Two)))^.25
9100     Ho=Alp*New
9110     Twoc=Tsteam-Qp/Ho
9120     IF ABS((Twoc-Two)/Twoc)>.001 THEN
9130        Two=Twoc
9140        GOTO 9040
9150     END IF
9160     Hi=Kcw/Di*Ci*Omega
9170     M=(Hi*P/(Km*A))^.5
9180     Fe1=FNTanh(M*L1)/(M*L1)
9190     Fe2=FNTanh(M*L2)/(M*L2)
9200  !
9210  ! Compute the Wilson data points for linear regression.
9220     X=Droot*New*L/(Omega*Kcw*(L+L1*Fe1+L2*Fe2))
9230     Y=New*(1.0/Uo-Rm*PI*Droot*L)
9240     Sumx=Sumx+X
9250     Sumy=Sumy+Y
9260     Sumx2=Sumx2+X*X
9270     Sumy2=Sumy2+Y*Y
9280     Sumxy=Sumxy+X*Y
9290  NEXT J
9300  !
9310  ! Compute the slope and intercept of the Modified Wilson plot.  Take the
9320  ! reciprocals and compute Alpc and Cic.  Compare with the last values of
9330  ! Alp and Ci.  If out of tolerance, average the values and repeat entire
9340  ! analysis with the revised values.
```

```
9350  Sxx=Sumx2-Sumx^2/Nrun
9360  Sxy=Sumxy-Sumx*Sumy/Nrun
9370  Xbar=Sumx/Nrun
9380  Ybar=Sumy/Nrun
9390  Slope=Sxy/Sxx
9400  Ntercept=Ybar-Slope*Xbar
9410  Cic=1.0/Slope
9420  Alpc=1.0/Ntercept
9430  Cerr=ABS((Cic-Ci)/Cic)
9440  Aerr=ABS((Alpc-Alp)/Alpc)
9450  Ci=(Ci+Cic)/2.0
9460  Alp=(Alp+Alpc)/2.0
9470  IF Cerr>.0005 OR Aerr>.0005 THEN GOTO 8880
9480  !
9490  ! Once final values of Ci and Alp are found, compute the regression
9500  ! coefficient of the Modified Wilson plot.  Find the enhancements for
9510  ! constant heat flux and constant temperature drop across the film.
9520  ! Print the results.
9530  Syy=Sumy2-Nrun*Ybar^2
9540  Sse=Syy-Slope*Sxy
9550  R=(1.0-Sse/Syy)^.5
9560  PRINTER IS 701
9570  PRINT USING "10X,""Wilson Plot regression coefficient = "",Z.3D";R
9580  PRINT USING "10X,""Ci (based on Petukhov-Popov)       = "",Z.3D";Ci
9590  PRINT USING "10X,""Alpha (based on Nusselt)           = "",Z.3D";Alp
9600  IF Ifg=1 THEN
9610     Et=Alp/Alpsm
9620     Eq=Et^(4.0/3.0)
9630     PRINT USING "10X,""Enhancement (constant heat flux)   = "",Z.3D";Eq
9640     PRINT USING "10X,""Enhancement (constant temp drop)   = "",Z.3D";Et
9650  END IF
9660  PRINT
9670  !
9680  ! Determine and print the final values of heat flux, Hi, and Ho for each
9690  ! data point.  Determine the power relationship between heat flux and Ho
9700  ! and print.
9710  PRINT USING "24X,""Overall     Outside     Inside"""
9720  PRINT USING "14X,""Coolant  Heat Xfer   Heat Xfer   Heat Xfer     Heat
           Steam"""
9730  PRINT USING "13X,""Velocity Coefficient Coefficient Coefficient    Flux
  Ts-Twall   Temp"""
9740 PRINT USING "2X,""Data  LMTD     Uw        Uo          Ho            Hi
   Qp          Txf"""
9750 PRINT USING "4X,""#  (degC)  (m/s)   (W/m^2-K)   (W/m^2-K)   (W/m^2-K)     (
W/m^2)    (degC)"""
9760  PRINT
9770  Txfavg=0.
9780  Hoavg=0.
```

```
9790  Qpavg=0.
9800  FOR J=1 TO Nrun
9810      Tsteam=Array(J-1,0)
9820      Kcw=Array(J-1,1)
9830      Qp=Array(J-1,2)
9840      Uo=Array(J-1,3)
9850      Omega=Array(J-1,4)
9860      Vcw=Array(J-1,5)
9870      Lmtd=Array(J-1,6)
9880      Hi=Kcw/Di*Ci*Omega
9890      M=(Hi*P/(Km*A))^.5
9900      Fe1=FNTanh(M*L1)/(M*L1)
9910      Fe2=FNTanh(M*L2)/(M*L2)
9920      Ho=1.0/(1.0/Uo-Droot*L/(Di*(L+L1*Fe1+L2*Fe2)*Hi)-Rm*L*PI*Droot)
9930      Txf=Qp/Ho
9940      PRINT USING "3X,DD,3X,DD.DD,3X,Z.DD,2X,4(MD.3DE,2X),1X,DD.DD";J,Lmtd,Vc
w,Uo,Ho,Hi,Qp,Txf
9950      Txfavg=Txfavg+Txf
9960      Hoavg=Hoavg+Ho
9970      Qpavg=Qpavg+Qp
9980  NEXT J
9990  Txfavg=Txfavg/Nrun
10000 Hoavg=Hoavg/Nrun
10010 Qpavg=Qpavg/Nrun
10020 PRINT USING "2X,""Avg"",29X,MD.3DE,14X,MD.3DE,3X,DD.DD";Hoavg,Qpavg,Txfavg
10030 SUBEND
10040 !
10050 !
10060 !
10070 SUB Merge
10080 ! This subroutine will merge two data files into a new data file or copy
10090 ! one file to another.
10100 DIM Array(27,8)
10110 INPUT "TYPE OF OPERATION? (0=Merge,1=Copy)";Ifile
10120 IF Ifile=0 THEN
10130     INPUT "GIVE THE NAME OF THE FIRST DATA FILE",D_file$
10140 ELSE
10150     INPUT "GIVE THE NAME OF THE FILE TO BE COPIED",D_file$
10160 END IF
10170 ASSIGN @File TO D_file$
10180 INPUT "ENTER THE NUMBER OF DATA POINTS",Nrun1
10190 ENTER @File;Ifg,Imc,Ipc
10200 ENTER @File;Fs,Fw,Fh
10210 ENTER @File;Di,Droot
10220 FOR J=1 TO Nrun1
10230     ENTER @File;Fm,T1,T2,Tsteam,Pgage,Pxdcr,Troom,Bvol,Bamp
10240     Array(J-1,0)=Fm
10250     Array(J-1,1)=T1
```

```
10260    Array(J-1,2)=T2
10270    Array(J-1,3)=Tsteam
10280    Array(J-1,4)=Pgage
10290    Array(J-1,5)=Pxdcr
10300    Array(J-1,6)=Troom
10310    Array(J-1,7)=Bvol
10320    Array(J-1,8)=Bamp
10330 NEXT J
10340 ASSIGN @File TO *
10350 IF Ifile=0 THEN
10360    INPUT "GIVE THE NAME OF THE SECOND DATA FILE",D_file$
10370    ASSIGN @File TO D_file$
10380    INPUT "ENTER THE NUMBER OF DATA POINTS",Nrun
10390    Nrun=Nrun+Nrun1-1
10400    ENTER @File;Ddd,Ddd,Ddd
10410    ENTER @File;Ddd,Ddd,Ddd
10420    ENTER @File;Ddd,Ddd
10430    FOR J=Nrun1 TO Nrun
10440       ENTER @File;Fm,T1,T2,Tsteam,Pgage,Pxdcr,Troom,Bvol,Bamp
10450       Array(J,0)=Fm
10460       Array(J,1)=T1
10470       Array(J,2)=T2
10480       Array(J,3)=Tsteam
10490       Array(J,4)=Pgage
10500       Array(J,5)=Pxdcr
10510       Array(J,6)=Troom
10520       Array(J,7)=Bvol
10530       Array(J,8)=Bamp
10540    NEXT J
10550    ASSIGN @File TO *
10560    Nrun=Nrun+1
10570 END IF
10580 IF Ifile=0 THEN
10590    INPUT "GIVE THE NAME OF THE MERGED DATA FILE",D_file$
10600 ELSE
10610    INPUT "GIVE THE NAME OF THE NEW DATA FILE",D_file$
10620    Nrun=Nrun1
10630 END IF
10640 CREATE BDAT D_file$,30
10650 ASSIGN @File TO D_file$
10660 OUTPUT @File;Ifg,Imc,Ipc
10670 OUTPUT @File;Fs,Fw,Fh
10680 OUTPUT @File;Di,Droot
10690 FOR J=1 TO Nrun
10700    Fm=Array(J-1,0)
10710    T1=Array(J-1,1)
10720    T2=Array(J-1,2)
10730    Tsteam=Array(J-1,3)
```

```
10740    Pgage=Array(J-1,4)
10750    Pxdcr=Array(J-1,5)
10760    Troom=Array(J-1,6)
10770    Bvol=Array(J-1,7)
10780    Bamp=Array(J-1,8)
10790    OUTPUT @File;Fm,T1,T2,Tsteam,Pgage,Pxdcr,Troom,Bvol,Bamp
10800 NEXT J
10810 ASSIGN @File TO *
10820 SUBEND
10830 !
10840 !
10850 !
10860 DEF FNRhostm(T)
10870 ! This function takes steam temp [degC] and returns density [kg/m^3].
10880 !
10890 COM /Rhostm/ C9(5)
10900 Ro=C9(0)
10910 FOR I=1 TO 5
10920    Ro=Ro*T+C9(I)
10930 NEXT I
10940 RETURN Ro
10950 FNEND
10960 !
10970 !
10980 !
10990 DEF FNTcouple(E)
11000 ! This function takes a thermocouple voltage [mV] and returns temperature
11010 ! [degC] using a generic type-T thermocouple correlation from Beckwith, T.
11020 ! G., Marangoni, R.D., and Lienhard, J.H., MECHANICAL MEASUREMENTS, (5th
11030 ! ed), Addison-Wesley: Reading, Ma, 1993, p. 684.
11040 !
11050 COM /Tcouple/ C10(3)
11060 T=0.
11070 FOR I=1 TO 4
11080    T=T+C10(I-1)*E^I
11090 NEXT I
11100 RETURN T
11110 FNEND
```

APPENDIX D. RAW AND PROCESSED DATA

Raw data was compiled for 20 experimental trials for each of two pressure conditions. Raw and processed data from accepted data trials follow.

```
        Program Name:                   DRPALL
        Raw data stored on file:        SSMTV3
        Data taken by:                  INCHECK
        Tube type:                      SMOOTH TUBE
        Tube material:                  STAINLESS-STEEL
        Thermal conductivity:            14.3 (W/m-K)
        Inside diameter:                 13.21 (mm)
        Root diameter:                   14.10 (mm)
        Pressure condition:             VACUUM

          Room    Inlet   Outlet   Steam    Gage    Xducer
    Flow  Temp    Temp    Temp     Temp     Press   Press    Volts   Current
   (pct) (degC)  (degC)  (degC)   (degC)   (KPa)   (KPa)     (V)

 1   80   19.63   17.46   18.03    48.7     11.0    10.8    198.0    1.04
 2   70   19.65   17.55   18.18    48.7     11.0    11.0    197.9    1.03
 3   60   19.66   17.62   18.32    48.6     11.0    10.9    198.2    1.03
 4   50   19.65   17.46   18.27    49.7     11.0    11.0    197.9    1.03
 5   40   19.67   17.49   18.43    48.6     11.0    10.9    197.9    1.04
 6   30   19.69   17.57   18.74    48.6     11.0    11.0    197.9    1.03
 7   20   19.67   17.59   19.13    48.7     11.0    11.0    198.0    1.04
 8   20   19.68   17.59   19.13    48.7     11.0    10.9    198.0    1.03
 9   30   19.69   17.54   18.71    48.6     10.9    10.9    198.0    1.04
10   40   19.71   17.35   18.30    48.7     11.0    11.1    197.9    1.04
11   50   19.68   17.29   18.09    48.5     11.0    11.1    198.3    1.02
12   60   19.71   17.31   18.01    48.7     11.0    11.0    198.0    1.04
13   70   19.68   17.47   18.05    48.6     10.9    11.0    198.4    1.02
14   80   19.72   17.49   18.06    48.8     11.0    11.1    197.5    1.02
```

```
Program Name:                  DRPALL
Raw data stored on file:       SSMTV3 .
Data taken by:                 INCHECK
Tube type:                     SMOOTH TUBE
Tube material:                 STAINLESS-STEEL
Thermal conductivity:           14.3 (W/m-K)
Inside diameter:                13.21 (mm)
Root diameter:                  14.10 (mm)
Pressure condition:            VACUUM
System power:                    6.81 (KW)
Steam velocity:                  1.97 (m/s)
This analysis includes end-fin effect
HEATEX insert installed in tube.

Wilson Plot regression coefficient = 0.998
Ci (based on Petukhov-Popov)       = 2.803
Alpha (based on Nusselt)           = 0.823

                        Overall     Outside     Inside
              Coolant  Heat Xfer   Heat Xfer   Heat Xfer     Heat
             Velocity Coefficient Coefficient Coefficient    Flux      Ts-Twall
Date   LMTD     Vw        Uo          Ho          Hi          Qp         Txf
  #  (degC)   (m/s)   (W/m^2-K)   (W/m^2-K)   (W/m^2-K)    (W/m^2)     (degC)

  1   31.02   4.11   6.707E+03   1.081E+04   4.344E+04   2.080E+05   19.25
  2   30.84   3.61   6.754E+03   1.128E+04   3.886E+04   2.083E+05   18.47
  3   30.65   3.11   6.517E+03   1.106E+04   3.437E+04   1.997E+05   18.07
  4   30.80   2.61   6.379E+03   1.126E+04   2.959E+04   1.964E+05   17.45
  5   30.63   2.11   6.107E+03   1.126E+04   2.475E+04   1.870E+05   16.61
  6   30.43   1.61   5.858E+03   1.176E+04   1.976E+04   1.783E+05   15.16
  7   30.29   1.10   5.338E+03   1.215E+04   1.450E+04   1.617E+05   13.31
  8   30.29   1.10   5.355E+03   1.224E+04   1.450E+04   1.622E+05   13.25
  9   30.48   1.61   5.842E+03   1.170E+04   1.975E+04   1.781E+05   15.22
 10   30.84   2.11   6.127E+03   1.134E+04   2.471E+04   1.890E+05   16.67
 11   30.92   2.61   6.366E+03   1.123E+04   2.953E+04   1.968E+05   17.53
 12   31.10   3.11   6.521E+03   1.108E+04   3.424E+04   2.028E+05   18.30
 13   30.82   3.61   6.561E+03   1.075E+04   3.892E+04   2.022E+05   18.81
 14   31.02   4.11   6.733E+03   1.087E+04   4.346E+04   2.089E+05   19.21
Avg                              1.134E+04               1.914E+05   16.95
```

```
Program Name:                  DRPALL
Raw data stored on file:       SSMTV4
Data taken by:                 INCHECK
Tube type:                     SMOOTH TUBE
Tube material:                 STAINLESS-STEEL
Thermal conductivity:           14.3 (W/m-K)
Inside diameter:                13.21 (mm)
Root diameter:                  14.10 (mm)
Pressure condition:            VACUUM

          Room    Inlet   Outlet   Steam    Gage   Xducer
   Flow   Temp    Temp    Temp     Temp     Press  Press    Volts  Current
  (pct) (degC)  (degC)  (degC)   (degC)   (KPa)  (KPa)     (V)

 1  80   19.76   17.66   18.22    48.7     10.9    11.0    198.1   1.04
 2  70   19.74   17.72   18.33    48.7     10.9    11.0    198.1   1.04
 3  60   19.78   17.81   18.50    48.5     10.9    11.0    198.0   1.04
 4  50   19.79   17.61   18.40    48.7     10.9    11.0    197.8   1.04
 5  40   19.80   17.68   18.61    48.6     10.8    11.0    197.9   1.04
 6  30   19.83   17.71   18.86    48.7     11.0    11.0    198.0   1.04
 7  20   19.81   17.80   19.33    48.7     11.0    11.0    198.1   1.04
 8  20   19.80   17.79   19.32    48.7     10.9    11.0    198.0   1.03
 9  30   19.81   17.58   18.73    48.5     10.9    10.9    197.9   1.04
10  40   19.81   17.49   18.44    48.5     11.0    11.0    198.0   1.04
11  50   19.83   17.45   18.25    48.6     11.0    11.0    198.1   1.04
12  60   19.82   17.44   18.14    48.7     11.0    11.0    198.0   1.04
13  70   19.82   17.58   18.20    48.7     11.0    11.0    198.2   1.04
14  80   19.86   17.59   18.15    48.6     11.0    11.0    198.0   1.04
```

```
Program Name:                  ORPALL
Raw data stored on file:       SSMTV4
Data taken by:                 INCHECK
Tube type:                     SMOOTH TUBE
Tube material:                 STAINLESS-STEEL
Thermal conductivity:           14.3 (W/m-K)
Inside diameter:                13.21 (mm)
Root diameter:                  14.10 (mm)
Pressure condition:            VACUUM
System power:                    6.81 (KW)
Steam velocity:                  1.97 (m/s)
This analysis includes end-fin effect
HEATEX insert installed in tube

Wilson Plot regression coefficient = 0.997
Ci (based on Petukhov-Popov)       = 2.857
Alpha (based on Nusselt)           = 0.808

                          Overall     Outside     Inside
               Coolant   Heat Xfer   Heat Xfer   Heat Xfer     Heat
              Velocity Coefficient Coefficient Coefficient     Flux      Ts-Twall
Data   LMTD      Vw         Uo          Ho          Hi          Qp          Txf
 #   (degC)    (m/s)   (W/m^2-K)   (W/m^2-K)   (W/m^2-K)    (W/m^2)      (degC)

  1   30.78    4.11    6.754E+03   1.087E+04   4.437E+04   2.079E+05    19.13
  2   30.66    3.61    6.479E+03   1.047E+04   3.977E+04   1.987E+05    18.98
  3   30.40    3.11    6.516E+03   1.098E+04   3.510E+04   1.981E+05    18.05
  4   30.68    2.61    6.261E+03   1.081E+04   3.020E+04   1.920E+05    17.76
  5   30.46    2.11    6.098E+03   1.112E+04   2.528E+04   1.858E+05    16.71
  6   30.41    1.61    5.785E+03   1.133E+04   2.016E+04   1.759E+05    15.52
  7   30.13    1.10    5.345E+03   1.196E+04   1.481E+04   1.610E+05    13.46
  8   30.14    1.10    5.338E+03   1.193E+04   1.481E+04   1.609E+05    13.49
  9   30.35    1.61    5.796E+03   1.139E+04   2.013E+04   1.759E+05    15.45
 10   30.67    2.11    6.165E+03   1.136E+04   2.522E+04   1.891E+05    16.65
 11   30.74    2.61    6.339E+03   1.106E+04   3.015E+04   1.949E+05    17.63
 12   30.90    3.11    6.455E+03   1.082E+04   3.495E+04   1.994E+05    18.44
 13   30.82    3.61    6.552E+03   1.065E+04   3.371E+04   2.019E+05    18.93
 14   30.76    4.11    6.689E+03   1.070E+04   4.434E+04   2.057E+05    19.22
Avg                                1.110E+04               1.891E+05    17.10
```

```
        Program Name:                DRPALL
        Raw data stored on file:     S16V1
        Data taken by:               INCHECK
        Tube type:                   RECTANGULAR FINNED TUBE
        Fin spacing, width, height:  1.50  1.00  0.16 (mm)
        Tube material:               STAINLESS-STEEL
        Thermal conductivity:         14.3 (W/m-K)
        Inside diameter:              13.20 (mm)
        Root diameter:                14.25 (mm)
        Pressure condition:          VACUUM

           Room    Inlet   Outlet   Steam     Gage   Xducer
     Flow  Temp    Temp    Temp     Tamp     Press   Press   Volts  Current
    (pct) (degC)  (degC)  (degC)   (degC)    (kPa)   (KPa)    (V)

 1   80   19.70   17.08   17.73     48.5     10.7    10.9   198.1    1.04
 2   70   19.71   17.17   17.90     48.7     11.0    11.1   198.1    1.04
 3   60   19.72   17.26   18.07     48.7     11.0    11.0   197.8    1.04
 4   50   19.75   17.12   18.04     48.6     11.0    11.0   197.9    1.03
 5   40   19.75   17.13   18.20     48.5     11.0    10.9   197.9    1.03
 6   30   19.73   17.20   18.51     48.6     11.0    11.0   197.9    1.03
 7   20   19.73   17.26   18.97     48.6     10.9    11.0   197.9    1.03
 8   20   19.74   17.24   18.95     48.6     10.9    11.0   198.4    1.03
 9   30   19.73   17.07   18.39     48.7     11.0    11.0   197.9    1.04
10   40   19.74   16.97   18.06     48.7     11.0    11.0   198.2    1.03
11   50   19.75   16.95   17.88     48.7     11.0    11.0   197.8    1.03
12   60   19.73   16.94   17.76     48.7     11.0    11.0   197.9    1.03
13   70   19.73   17.12   17.84     48.7     11.0    11.0   198.0    1.03
14   80   19.73   17.14   17.80     48.7     11.0    11.0   198.0    1.03
```

```
Program Name:                  DRPALL
Raw data stored on file:       616V1
Data taken by:                 INCHECK
Tube type:                     RECTANGULAR FINNED TUBE
Fin spacing, width, height:    1.50  1.00  0.16 (mm)
Tube material:                 STAINLESS-STEEL
Thermal conductivity:           14.3 (W/m-K)
Inside diameter:                13.20 (mm)
Root diameter:                  14.25 (mm)
Pressure condition:            VACUUM
System power:                    6.81 (KW)
Steam velocity:                  1.97 (m/s)
This analysis includes end-fin effect
HEATEX insert installed in tube
Enhancements based on comparison to Incheck smooth tube data

Wilson Plot regression coefficient = 0.998
Ci (based on Petukhov-Popov)       = 2.714
Alpha (based on Nusselt)           = 1.088
Enhancement (constant heat flux)   = 1.469
Enhancement (constant temp drop)   = 1.335

                      Overall      Outside      Inside
           Coolant   Heat Xfer    Heat Xfer    Heat Xfer      Heat
          Velocity  Coefficient  Coefficient  Coefficient     Flux       Ts-Twall
Data  LMTD    Vw        Uo           Ho           Hi           Qp          Txf
 #  (degC)  (m/s)   (W/m^2-K)    (W/m^2-K)    (W/m^2-K)    (W/m^2)      (degC)

  1  31.15   4.12   7.643E+03    1.490E+04    4.196E+04    2.381E+05    15.98
  2  31.19   3.62   7.626E+03    1.550E+04    3.763E+04    2.378E+05    15.34
  3  31.02   3.12   7.466E+03    1.574E+04    3.321E+04    2.316E+05    14.71
  4  30.99   2.61   7.239E+03    1.599E+04    2.859E+04    2.243E+05    14.03
  5  30.87   2.11   6.831E+03    1.575E+04    2.392E+04    2.109E+05    13.39
  6  30.72   1.61   6.417E+03    1.622E+04    1.909E+04    1.972E+05    12.16
  7  30.52   1.11   5.832E+03    1.750E+04    1.402E+04    1.780E+05    10.17
  8  30.53   1.11   5.830E+03    1.748E+04    1.401E+04    1.780E+05    10.18
  9  30.93   1.61   6.439E+03    1.638E+04    1.906E+04    1.992E+05    12.16
 10  31.15   2.11   6.909E+03    1.619E+04    2.387E+04    2.152E+05    13.29
 11  31.30   2.61   7.171E+03    1.568E+04    2.854E+04    2.245E+05    14.32
 12  31.31   3.12   7.490E+03    1.588E+04    3.308E+04    2.345E+05    14.77
 13  31.20   3.62   7.541E+03    1.516E+04    3.760E+04    2.353E+05    15.52
 14  31.23   4.12   7.766E+03    1.537E+04    4.199E+04    2.425E+05    15.78
Avg                              1.598E+04                 2.176E+05    13.70
```

```
        Program Name:                    DRPALL
        Raw data stored on file:         S16V2
        Data taken by:                   INCHECK
        Tube type:                       RECTANGULAR FINNED TUBE
        Fin spacing, width, height:      1.50  1.00  0.15 (mm)
        Tube material:                   STAINLESS-STEEL
        Thermal conductivity:             14.3 (W/m-K)
        Inside diameter:                  13.20 (mm)
        Root diameter:                    14.25 (mm)
        Pressure condition:              VACUUM

              Room    Inlet   Outlet   Steam    Gage    Xducer
       Flow   Temp    Temp    Temp     Temp     Press   Press    Volts   Current
      (pct) (degC)  (degC)  (degC)   (degC)   (KPa)   (KPa)     (V)

  1    80    19.75   17.29   17.94    48.7     11.0    10.9    197.9    1.03
  2    70    19.75   17.36   18.08    48.5     10.8    10.9    197.9    1.02
  3    60    19.77   17.44   18.24    48.7     10.7    11.0    197.5    1.03
  4    50    19.78   17.28   18.20    48.6     11.0    11.0    198.1    1.03
  5    40    19.77   17.29   18.36    48.6     10.9    11.0    197.9    1.03
  6    30    19.79   17.34   18.65    48.8     11.0    10.9    198.0    1.03
  7    20    19.77   17.42   19.13    48.7     11.0    11.0    197.9    1.03
  8    20    19.79   17.40   19.11    48.6     10.9    10.8    197.9    1.03
  9    30    19.77   17.23   18.54    48.7     10.9    10.8    198.0    1.03
 10    40    19.78   17.11   18.19    48.7     11.0    10.8    198.0    1.03
 11    50    19.79   17.08   18.01    48.7     10.9    10.8    198.1    1.03
 12    60    19.79   17.06   17.88    48.7     10.9    10.8    197.8    1.03
 13    70    19.79   17.22   17.94    48.6     10.9    10.7    197.8    1.03
 14    80    19.79   17.22   17.88    48.7     10.9    10.8    198.1    1.03
```

```
Program Name:                    DRPALL
Raw data stored on file:         S16V2
Data taken by:                   INCHECK
Tube type:                       RECTANGULAR FINNED TUBE
Fin spacing, width, height:      1.50  1.00  0.16 (mm)
Tube material:                   STAINLESS-STEEL
Thermal conductivity:             14.3 (W/m-K)
Inside diameter:                  13.20 (mm)
Root diameter:                    14.25 (mm)
Pressure condition:              VACUUM
System power:                      6.80 (KW)
Steam velocity:                    1.97 (m/s)
This analysis includes end-fin effect
HEATEX insert installed in tube
Enhancements based on comparison to Incheck smooth tube data

Wilson Plot regression coefficient = 0.999
Ci (based on Petukhov-Popov)       = 3.694
Alpha (based on Nusselt)           = 1.068
Enhancement (constant heat flux)   = 1.471
Enhancement (constant temp drop)   = 1.336

                     Overall     Outside      Inside
          Coolant   Heat Xfer   Heat Xfer   Heat Xfer     Heat
         Velocity Coefficient Coefficient Coefficient     Flux     Ts-Twall
Data   LMTD   Vw       Uo          Ho          Hi          Qp        - Txf
 #   (degC)  (m/s)  (W/m^2-K)   (W/m^2-K)   (W/m^2-K)    (W/m^2)    (degC)

 1   31.06   4.12   7.745E+03   1.532E+04   4.175E+04   2.406E+05   15.70
 2   30.80   3.62   7.605E+03   1.545E+04   3.743E+04   2.343E+05   15.16
 3   30.88   3.12   7.422E+03   1.559E+04   3.303E+04   2.292E+05   14.70
 4   30.89   2.61   7.245E+03   1.607E+04   2.844E+04   2.238E+05   13.93
 5   30.92   2.11   6.802E+03   1.566E+04   2.378E+04   2.097E+05   13.39
 6   30.77   1.61   6.431E+03   1.639E+04   1.898E+04   1.979E+05   12.07
 7   30.44   1.11   5.842E+03   1.771E+04   1.394E+04   1.778E+05   10.04
 8   30.36   1.11   5.836E+03   1.766E+04   1.394E+04   1.772E+05   10.03
 9   30.85   1.61   6.395E+03   1.617E+04   1.895E+04   1.973E+05   12.20
10   31.09   2.11   6.854E+03   1.596E+04   2.373E+04   2.131E+05   13.35
11   31.16   2.61   7.195E+03   1.585E+04   2.837E+04   2.242E+05   14.14
12   31.25   3.12   7.463E+03   1.581E+04   3.288E+04   2.332E+05   14.75
13   31.04   3.62   7.615E+03   1.550E+04   3.737E+04   2.364E+05   15.25
14   31.19   4.12   7.746E+03   1.533E+04   4.171E+04   2.416E+05   15.76
Avg                             1.603E+04               2.169E+05   13.61
```

```
Program Name:                    DRPALL
Raw data stored on file:         S28V1
Data taken by:                   INCHECK
Tube type:                       RECTANGULAR FINNED TUBE
Fin spacing, width, height:      1.50  1.00  0.28 (mm)
Tube material:                   STAINLESS-STEEL
Thermal conductivity:             14.3 (W/m-K)
Inside diameter:                  13.15 (mm)
Root diameter:                    14.23 (mm)
Pressure condition:              VACUUM

              Room     Inlet    Outlet    Steam     Gage    Xducer
       Flow   Temp     Temp     Temp      Temp      Press   Press    Volts   Current
      (pct) (degC)   (degC)   (degC)    (degC)    (KPa)   (KPa)     (V)

  1    80    20.02    17.24    17.93     48.9     11.0    11.2    198.1    1.03
  2    70    19.97    17.39    18.14     48.7     10.9    11.1    198.1    1.04
  3    60    20.01    17.52    18.33     48.6     11.0    11.0    198.1    1.03
  4    50    20.03    17.41    18.34     48.8     11.0    11.1    198.0    1.03
  5    40    20.05    17.44    18.54     48.7     11.0    11.1    198.0    1.04
  6    30    20.04    17.56    18.90     48.6     11.0    11.0    198.0    1.04
  7    20    20.02    17.69    19.41     48.7     11.0    11.1    198.1    1.03
  8    20    20.02    17.70    19.42     48.7     11.0    11.0    198.0    1.04
  9    30    20.03    17.53    18.87     48.7     11.0    11.0    198.1    1.04
 10    40    20.04    17.46    18.57     48.7     11.0    11.1    197.9    1.03
 11    50    20.03    17.45    18.39     48.6     11.0    11.0    198.0    1.03
 12    60    20.05    17.47    18.29     48.6     11.0    11.0    198.1    1.03
 13    70    20.05    17.61    18.35     48.6     11.0    11.0    197.9    1.03
 14    80    20.04    17.65    18.32     48.7     11.0    11.1    197.8    1.03
```

```
Program Name:                  DRPALL
Raw data stored on file:       S28V1
Data taken by:                 INCHECK
Tube type:                     RECTANGULAR FINNED TUBE
Fin spacing, width, height:    1.50  1.00  0.28 (mm)
Tube material:                 STAINLESS-STEEL
Thermal conductivity:           14.3 (W/m-K)
Inside diameter:                13.15 (mm)
Root diameter:                  14.23 (mm)
Pressure condition:            VACUUM
System power:                    6.81 (KW)
Steam velocity:                  1.97 (m/s)
This analysis includes end-fin effect
HEATEX insert installed in tube
Enhancements based on comparison to Incheck smooth tube data

Wilson Plot regression coefficient = 0.999
Ci (based on Petukhov-Popov)       = 2.671
Alpha (based on Nusselt)           = 1.170
Enhancement (constant heat flux)   = 1.620
Enhancement (constant temp drop)   = 1.436

                          Overall      Outside      Inside
               Coolant   Heat Xfer    Heat Xfer    Heat Xfer      Heat
              Velocity  Coefficient  Coefficient  Coefficient     Flux      Ts-Twall
Data   LMTD      Vw         Uo           Ho           Hi           Qp         Txf
 #    (degC)   (m/s)    (W/m^2-K)    (W/m^2-K)    (W/m^2-K)     (W/m^2)     (degC)

  1    31.38    4.15    8.038E+03    1.685E+04    4.187E+04    2.522E+05    14.97
  2    30.96    3.65    7.956E+03    1.734E+04    3.740E+04    2.463E+05    14.21
  3    30.66    3.14    7.620E+03    1.683E+04    3.301E+04    2.337E+05    13.88
  4    30.93    2.63    7.360E+03    1.700E+04    2.844E+04    2.276E+05    13.39
  5    30.74    2.13    7.082E+03    1.759E+04    2.379E+04    2.177E+05    12.38
  6    30.39    1.62    6.642E+03    1.822E+04    1.900E+04    2.019E+05    11.08
  7    30.16    1.11    5.948E+03    1.915E+04    1.396E+04    1.794E+05     9.37
  8    30.10    1.11    5.960E+03    1.927E+04    1.397E+04    1.794E+05     9.31
  9    30.48    1.62    6.635E+03    1.818E+04    1.899E+04    2.023E+05    11.13
 10    30.69    2.13    7.128E+03    1.780E+04    2.380E+04    2.187E+05    12.24
 11    30.71    2.63    7.450E+03    1.748E+04    2.845E+04    2.288E+05    13.09
 12    30.75    3.14    7.674E+03    1.710E+04    3.209E+04    2.360E+05    13.80
 13    30.67    3.65    7.878E+03    1.690E+04    3.749E+04    2.416E+05    14.26
 14    30.72    4.15    7.987E+03    1.660E+04    4.187E+04    2.454E+05    14.78
Avg                                  1.760E+04                 2.222E+05    12.71
```

```
        Program Name:                   DRPALL
        Raw data stored on file:        S28V2
        Data taken by:                  INCHECK
        Tube type:                      RECTANGULAR FINNED TUBE
        Fin spacing, width, height:     1.50  1.00  0.28 (mm)
        Tube material:                  STAINLESS-STEEL
        Thermal conductivity:            14.3 (W/m-K)
        Inside diameter:                 13.15 (mm)
        Root diameter:                   14.23 (mm)
        Pressure condition:             VACUUM

             Room    Inlet   Outlet   Steam    Gage    Xducer
      Flow   Temp    Temp     Temp    Temp     Press   Press    Volts   Current
     (pct) (degC)   (degC)   (degC)  (dagC)   (KPa)   (KPa)     (V)

  1   80    19.91   17.27    17.95    48.7     10.8    11.1    198.1    1.03
  2   70    19.93   17.39    18.13    48.7     11.0    11.0    198.1    1.03
  3   60    19.82   17.54    18.36    48.7     11.0    11.2    197.9    1.04
  4   50    19.82   17.41    18.34    48.7     11.0    11.1    198.0    1.03
  5   40    19.78   17.46    18.55    48.7     11.0    11.2    198.0    1.03
  6   30    19.79   17.52    18.84    48.7     11.0    11.2    198.0    1.03
  7   20    19.88   17.65    19.34    48.8     11.0    11.3    198.0    1.03
  8   20    19.89   17.65    19.35    48.8     11.0    11.2    198.1    1.04
  9   30    19.90   17.54    18.85    48.7     11.0    11.0    198.1    1.03
 10   40    19.89   17.47    18.54    48.6     11.0    11.0    198.1    1.03
 11   50    19.89   17.43    18.34    48.7     10.9    11.2    198.1    1.04
 12   60    19.92   17.44    18.26    48.7     11.0    11.2    198.1    1.03
 13   70    19.93   17.67    18.40    48.7     10.9    11.2    198.0    1.03
 14   80    19.91   17.69    18.35    48.6     11.0    11.1    198.0    1.03
```

```
Program Name:                    DRPALL
Raw data stored on file:         S28V2
Data taken by:                   INCHECK
Tube type:                       RECTANGULAR FINNED TUBE
Fin spacing, width, height:      1.50  1.00  0.29 (mm)
Tube material:                   STAINLESS-STEEL
Thermal conductivity:             14.3 (W/m-K)
Inside diameter:                  13.15 (mm)
Root diameter:                    14.23 (mm)
Pressure condition:              VACUUM
System power:                      6.81 (KW)
Steam velocity:                    1.97 (m/s)
This analysis includes end-fin affect
HEATEX insert installed in tube
Enhancements based on comparison to Incheck smooth tube data

Wilson Plot regression coefficient = 0.999
Ci (based on Petukhov-Popov)       = 2.555
Alpha (based on Nusselt)           = 1.161
Enhancement (constant heat flux)   = 1.603
Enhancement (constant temp drop)   = 1.424

                      Overall     Outside     Inside
              Coolant Heat Xfer   Heat Xfer   Heat Xfer      Heat
             Velocity Coefficient Coefficient Coefficient    Flux       Ts-Twall
Data   LMTD     Vw       Uo          Ho          Hi           Qp          Txf
 #   (degC)   (m/s)  (W/m^2-K)   (W/m^2-K)   (W/m^2-K)    (W/m^2)     (degC)

  1   31.15   4.15   7.968E+03   1.687E+04   3.988E+04   2.482E+05    14.71
  2   30.98   3.65   7.765E+03   1.681E+04   3.577E+04   2.406E+05    14.31
  3   30.78   3.14   7.617E+03   1.724E+04   3.159E+04   2.344E+05    13.60
  4   30.82   2.63   7.348E+03   1.744E+04   2.720E+04   2.265E+05    12.99
  5   30.65   2.13   7.006E+03   1.775E+04   2.277E+04   2.149E+05    12.10
  6   30.54   1.62   6.541E+03   1.831E+04   1.817E+04   1.998E+05    10.91
  7   30.25   1.11   5.823E+03   1.911E+04   1.335E+04   1.761E+05     9.22
  8   30.28   1.11   5.842E+03   1.931E+04   1.335E+04   1.769E+05     9.16
  9   30.46   1.62   6.482E+03   1.785E+04   1.817E+04   1.975E+05    11.06
 10   30.57   2.13   6.930E+03   1.727E+04   2.277E+04   2.119E+05    12.27
 11   30.77   2.63   7.239E+03   1.683E+04   2.721E+04   2.228E+05    13.24
 12   30.86   3.14   7.547E+03   1.690E+04   3.155E+04   2.329E+05    13.79
 13   30.66   3.65   7.849E+03   1.719E+04   3.589E+04   2.407E+05    14.00
 14   30.62   4.15   7.865E+03   1.638E+04   4.007E+04   2.408E+05    14.70
Avg                              1.752E+04               2.188E+05    12.58
```

```
           Program Name:                  DRPALL
           Raw data stored on file:       S28V3
           Data taken by:                 INCHECK
           Tube type:                     RECTANGULAR FINNED TUBE
           Fin spacing, width, height:    1.50  1.00  0.28 (mm)
           Tube material:                 STAINLESS-STEEL
           Thermal conductivity:           14.3 (W/m-K)
           Inside diameter:                13.15 (mm)
           Root diameter:                  14.23 (mm)
           Pressure condition:            VACUUM

              Room     Inlet    Outlet    Steam     Gage    Xducer
      Flow    Temp     Temp     Temp      Temp      Press   Press     Volts   Current
      (pct) (degC)   (degC)   (degC)    (degC)    (KPa)   (KPa)      (V)

  1    80    19.23    16.85    17.53     48.7      11.1    11.1     198.0    1.03
  2    70    19.24    16.98    17.71     48.7      11.2    11.1     198.1    1.03
  3    60    19.26    17.10    17.92     48.5      11.2    11.1     198.1    1.03
  4    50    19.26    16.95    17.88     48.7      11.3    11.1     198.1    1.03
  5    40    19.27    17.02    18.10     48.6      11.2    11.1     198.1    1.03
  6    30    19.28    17.07    18.40     48.8      11.3    11.2     198.1    1.03
  7    20    19.28    17.21    18.93     48.7      11.2    11.2     198.2    1.04
  8    20    19.28    17.21    18.93     48.7      11.3    11.1     198.1    1.03
  9    30    19.30    17.09    18.40     48.7      11.2    11.2     197.9    1.03
 10    40    19.30    16.96    18.05     48.6      11.3    11.1     197.9    1.03
 11    50    19.31    16.93    17.87     48.7      11.3    11.3     198.1    1.03
 12    60    19.30    16.94    17.76     48.6      11.2    11.1     197.9    1.03
 13    70    19.33    17.14    17.87     48.6      11.2    11.1     198.0    1.04
 14    80    19.34    17.17    17.85     48.7      11.2    11.1     198.0    1.04
```

```
Program Name:                     DRPALL
Raw data stored on file:          S28V3
Data taken by:                    INCHECK.
Tube type:                        RECTANGULAR FINNED TUBE
Fin spacing, width, height:       1.50  1.00  0.28 (mm)
Tube material:                    STAINLESS-STEEL
Thermal conductivity:              14.3 (W/m-K)
Inside diameter:                   13.15 (mm)
Root diameter:                     14.23 (mm)
Pressure condition:               VACUUM
System power:                       6.81 (KW)
Steam velocity:                     1.97 (m/s)
This analysis includes end-fin effect
HEATEX insert installed in tube
Enhancements based on comparison to Incheck smooth tube data

Wilson Plot regression coefficient = 0.999
Ci (based on Petukhov-Popov)       = 2.611
Alpha (based on Nusselt)           = 1.134
Enhancement (constant heat flux)   = 1.554
Enhancement (constant temp drop)   = 1.392

                          Overall      Outside     Inside
              Coolant   Heat Xfer    Heat Xfer   Heat Xfer      Heat
             Velocity  Coefficient  Coefficient Coefficient     Flux      Ts-Twall
Data   LMTD     Vw         Uo           Ho          Hi           Qo          Txf
 #   (degC)   (m/s)    (W/m^2-K)    (W/m^2-K)   (W/m^2-K)     (W/m^2)     (degC)

  1   31.52    4.15    7.849E+03    1.623E+04   4.054E+04    2.474E+05    15.24
  2   31.32    3.65    7.649E+03    1.615E+04   3.638E+04    2.396E+05    14.83
  3   31.05    3.14    7.547E+03    1.673E+04   3.211E+04    2.344E+05    14.01
  4   31.29    2.63    7.165E+03    1.627E+04   2.765E+04    2.242E+05    13.78
  5   31.07    2.13    6.843E+03    1.653E+04   2.314E+04    2.126E+05    12.87
  6   31.10    1.62    6.453E+03    1.734E+04   1.846E+04    2.007E+05    11.57
  7   30.68    1.11    5.820E+03    1.861E+04   1.357E+04    1.784E+05     9.59
  8   30.59    1.11    5.838E+03    1.879E+04   1.357E+04    1.786E+05     9.50
  9   30.93    1.62    6.427E+03    1.715E+04   1.847E+04    1.988E+05    11.59
 10   31.12    2.13    6.923E+03    1.701E+04   2.312E+04    2.154E+05    12.66
 11   31.30    2.63    7.253E+03    1.673E+04   2.764E+04    2.270E+05    13.57
 12   31.29    3.14    7.474E+03    1.639E+04   3.205E+04    2.339E+05    14.27
 13   31.15    3.65    7.723E+03    1.647E+04   3.644E+04    2.406E+05    14.61
 14   31.21    4.15    7.879E+03    1.633E+04   4.070E+04    2.459E+05    15.06
Avg                                 1.691E+04                2.198E+05    13.08
```

```
        Program Name:                    DRPALL
        Raw data stored on file:         S38V2
        Data taken by:                   INCHECK
        Tube type:                       RECTANGULAR FINNED TUBE
        Fin spacing, width, height:      1.50  1.00  0.38 (mm)
        Tube material:                   STAINLESS-STEEL
        Thermal conductivity:             14.3 (W/m-K)
        Inside diameter:                  13.08 (mm)
        Root diameter:                    14.28 (mm)
        Pressure condition:              VACUUM

              Room     Inlet   Outlet    Steam     Gage   Xducer
       Flow   Temp     Temp     Temp     Temp     Press   Press    Volts   Current
      (pct) (degC)   (degC)   (degC)   (degC)    (KPa)   (KPa)     (V)

   1    80   20.43    17.93    18.52     48.7     11.0    10.9    198.0    1.04
   2    70   20.44    18.01    18.65     48.6     10.9    10.9    198.0    1.04
   3    60   20.44    18.12    18.84     48.7     10.8    10.9    198.1    1.04
   4    50   20.45    17.98    19.80     48.6     10.9    10.9    198.0    1.04
   5    40   20.44    18.01    18.97     48.7     10.9    10.9    198.2    1.04
   6    30   20.45    18.04    19.21     48.6     10.8    10.9    198.0    1.04
   7    20   20.45    18.13    19.68     48.8     10.9    10.9    198.2    1.04
   8    20   20.44    18.13    19.68     48.7     10.9    10.9    198.1    1.04
   9    30   20.46    18.02    19.20     48.7     10.9    10.9    198.2    1.04
  10    40   20.45    17.91    18.87     48.6     10.8    10.9    198.1    1.04
  11    50   20.46    17.84    18.66     48.6     10.8    10.9    198.0    1.04
  12    60   20.47    17.83    18.55     48.6     10.8    10.9    198.1    1.04
  13    70   20.48    18.00    18.65     48.7     10.8    10.9    198.1    1.04
  14    80   20.50    18.05    18.54     48.7     10.8    10.9    198.1    1.04
```

```
Program Name:                      DRPALL
Raw data stored on file:           S38V2
Data taken by:                     INCHECK
Tube type:                         RECTANGULAR FINNED TUBE
Fin spacing, width, height:        1.50  1.00  0.38 (mm)
Tube material:                     STAINLESS-STEEL
Thermal conductivity:               14.3 (W/m-K)
Inside diameter:                    13.08 (mm)
Root diameter:                      14.29 (mm)
Pressure condition:                VACUUM
System power:                        6.81 (KW)
Steam velocity:                      1.97 (m/s)
This analysis includes end-fin effect
HEATEX insert installed in tube
Enhancements based on comparison to Incheck smooth tube data

Wilson Plot regression coefficient = 0.999
Ci (based on Petukhov-Popov)       = 2.624
Alpha (based on Nusselt)           = 0.974
Enhancement (constant heat flux)   = 1.268
Enhancement (constant temp drop)   = 1.195

                                Overall    Outside     Inside
                  Coolant     Heat Xfer   Heat Xfer   Heat Xfer      Heat
                 Velocity Coefficient Coefficient Coefficient      Flux      Ts-Twall
Data   LMTD        Vw          Uo          Ho          Hi           Qp          Txf
 #    (degC)     (m/s)    (W/m^2-K)   (W/m^2-K)   (W/m^2-K)     (W/m^2)      (degC)

 1    30.50      4.20     7.005E+03   1.379E+04   4.156E+04    2.136E+05     15.49
 2    30.32      3.69     6.869E+03   1.383E+04   3.735E+04    2.083E+05     15.07
 3    30.19      3.17     6.791E+03   1.425E+04   3.297E+04    2.050E+05     14.39
 4    30.25      2.66     6.546E+03   1.420E+04   2.839E+04    1.980E+05     13.94
 5    30.18      2.15     6.262E+03   1.431E+04   2.375E+04    1.890E+05     13.21
 6    30.00      1.64     5.877E+03   1.452E+04   1.894E+04    1.763E+05     12.14
 7    29.84      1.13     5.382E+03   1.562E+04   1.391E+04    1.606E+05     10.28
 8    29.81      1.13     5.390E+03   1.569E+04   1.391E+04    1.607E+05     10.24
 9    30.05      1.64     5.912E+03   1.474E+04   1.894E+04    1.776E+05     12.05
10    30.18      2.15     6.269E+03   1.435E+04   2.372E+04    1.892E+05     13.18
11    30.38      2.66     6.486E+03   1.394E+04   2.834E+04    1.971E+05     14.14
12    30.45      3.17     6.711E+03   1.392E+04   3.286E+04    2.044E+05     14.68
13    30.35      3.69     6.894E+03   1.392E+04   3.735E+04    2.092E+05     15.03
14    30.33      4.20     7.015E+03   1.382E+04   4.172E+04    2.128E+05     15.39
Avg                                   1.436E+04                1.930E+05     13.52
```

```
          Program Name:                 DRPALL
          Raw data stored on file:      S38V3
          Data taken by:                INCHECK
          Tube type:                    RECTANGULAR FINNED TUBE
          Fin spacing, width, height:   1.50  1.00  0.38 (mm)
          Tube material:                STAINLESS-STEEL
          Thermal conductivity:          14.3 (W/m-K)
          Inside diameter:               13.08 (mm)
          Root diameter:                 14.29 (mm)
          Pressure condition:           VACUUM

              Room     Inlet   Outlet    Steam     Gage   Xducer
       Flow   Temp     Temp    Temp      Temp      Press  Press     Volts   Current
      (pct) (degC)   (degC)  (degC)    (degC)     (KPa)  (KPa)     (V)

  1    80    20.58    17.70   18.30     48.8      10.5    11.1    197.9    1.03
  2    70    20.58    17.80   18.46     49.0      10.3    11.3    197.9    1.03
  3    60    20.60    17.93   18.66     48.8      10.5    11.2    198.0    1.03
  4    50    20.62    17.79   18.62     48.5      10.5    11.1    198.0    1.03
  5    40    20.61    17.88   18.85     48.7      10.5    11.2    198.0    1.03
  6    30    20.60    17.92   19.13     48.7      10.5    11.2    198.0    1.03
  7    20    20.60    18.10   19.66     48.7      10.5    11.2    198.4    1.04
  8    20    20.61    18.09   19.65     48.6      10.5    11.1    197.8    1.03
  9    30    20.60    17.93   19.12     48.6      10.5    11.1    198.1    1.03
 10    40    20.61    17.83   18.81     48.6      10.3    11.2    198.3    1.03
 11    50    20.65    17.77   18.60     48.6      10.5    11.2    198.1    1.03
 12    60    20.69    17.77   18.50     48.7      10.5    11.2    198.0    1.03
 13    70    20.73    17.94   18.60     48.6      10.5    11.1    198.1    1.03
 14    80    20.73    17.95   18.54     48.7      10.5    11.2    198.1    1.03
```

```
Program Name:                   DRPALL
Raw data stored on file:        S38V3
Data taken by:                  INCHECK
Tube type:                      RECTANGULAR FINNED TUBE
Fin spacing, width, height:     1.50  1.00  0.38 (mm)
Tube material:                  STAINLESS-STEEL
Thermal conductivity:            14.3 (W/m-K)
Inside diameter:                 13.08 (mm)
Root diameter:                   14.29 (mm)
Pressure condition:             VACUUM
System power:                     6.81 (KW)
Steam velocity:                  1.97 (m/s)
This analysis includes end-fin affect
HEATEX insert installed in tube
Enhancements based on comparison to Incheck smooth tube data

Wilson Plot regression coefficient = 0.999
Ci (based on Petukhov-Popov)       = 2.632
Alpha (based on Nusselt)           = 0.987
Enhancement (constant heat flux)   = 1.291
Enhancement (constant temp drop)   = 1.211

                         Overall    Outside     Inside
               Coolant  Heat Xfer  Heat Xfer   Heat Xfer     Heat
              Velocity Coefficient Coefficient Coefficient   Flux      Ts-Twall
Data   LMTD      Vw        Uo         Ho          Hi          Qp         Txf
 #   (degC)    (m/s)   (W/m^2-K)  (W/m^2-K)   (W/m^2-K)    (W/m^2)     (degC)

 1    30.79    4.20    7.004E+03  1.379E+04   4.166E+04   2.157E+05    15.64
 2    30.85    3.69    6.903E+03  1.396E+04   3.737E+04   2.129E+05    15.25
 3    30.54    3.17    6.782E+03  1.421E+04   3.299E+04   2.071E+05    14.58
 4    30.40    2.66    6.594E+03  1.443E+04   2.841E+04   2.005E+05    13.89
 5    30.38    2.15    6.265E+03  1.431E+04   2.378E+04   1.903E+05    13.30
 6    30.17    1.64    5.985E+03  1.518E+04   1.897E+04   1.806E+05    11.90
 7    29.86    1.13    5.400E+03  1.573E+04   1.395E+04   1.612E+05    10.25
 8    29.74    1.13    5.429E+03  1.598E+04   1.395E+04   1.614E+05    10.11
 9    30.06    1.64    5.931E+03  1.484E+04   1.897E+04   1.783E+05    12.01
10    30.31    2.15    6.284E+03  1.441E+04   2.377E+04   1.904E+05    13.21
11    30.43    2.66    6.569E+03  1.431E+04   2.840E+04   1.999E+05    13.97
12    30.59    3.17    6.803E+03  1.431E+04   3.293E+04   2.081E+05    14.54
13    30.33    3.69    7.014E+03  1.441E+04   3.743E+04   2.127E+05    14.76
14    30.45    4.20    7.056E+03  1.397E+04   4.178E+04   2.149E+05    15.38
Avg                               1.456E+04               1.953E+05    13.49
```

```
        Program Name:                  DRPALL
        Raw data stored on file:       S48V1
        Data taken by:                 INCHECK
        Tube type:                     RECTANGULAR FINNED TUBE
        Fin spacing, width, height:    1.50  1.00  0.48 (mm)
        Tube material:                 STAINLESS-STEEL
        Thermal conductivity:           14.3 (W/m-K)
        Inside diameter:                13.11 (mm)
        Root diameter:                  14.26 (mm)
        Pressure condition:            VACUUM

           Room    Inlet   Outlet   Steam    Gage    Xducer
     Flow  Temp    Temp    Temp     Temp     Press   Press    Volts   Current
    (pct) (degC)  (degC)  (degC)   (degC)   (KPa)   (KPa)     (V)

 1   80   20.58   17.11   17.71    48.9     10.7    11.2    184.7     .94
 2   70   20.58   17.28   17.93    48.6     10.5    11.0    185.2     .94
 3   60   20.57   17.41   18.14    48.6     10.6    11.1    185.7     .94
 4   50   20.57   17.32   18.14    48.7     10.6    11.1    185.1     .93
 5   40   20.60   17.43   18.39    48.6     10.5    11.1    184.9     .94
 6   30   20.58   17.55   18.72    48.7     10.6    11.1    184.9     .94
 7   20   20.57   17.74   19.27    48.7     10.5    11.1    185.0     .94
 8   20   20.60   17.77   19.30    48.7     10.5    11.1    185.0     .94
 9   30   20.59   17.59   18.75    48.6     10.6    11.1    185.1     .94
10   40   20.60   17.42   18.38    48.7     10.7    11.1    185.1     .94
11   50   20.60   17.35   18.17    48.6     10.6    11.1    185.0     .94
12   60   20.60   17.56   18.27    48.7     10.5    11.1    185.0     .94
13   70   20.60   17.55   18.19    48.7     10.5    11.1    185.0     .94
14   80   20.57   17.57   18.16    48.7     10.7    11.1    185.1     .94
```

```
Program Name:                     DRPALL
Raw data stored on file:          S48V1
Data taken by:                    INCHECK
Tube type:                        RECTANGULAR FINNED TUBE
Fin spacing, width, height:       1.50  1.00  0.48 (mm)
Tube material:                    STAINLESS-STEEL
Thermal conductivity:              14.3 (W/m-K)
Inside diameter:                   13.11 (mm)
Root diameter:                     14.26 (mm)
Pressure condition:               VACUUM
System power:                      5.85 (KW)
Steam velocity:                    1.71 (m/s)
This analysis includes end-fin effect
HEATEX insert installed in tube
Enhancements based on comparison to Incheck smooth tube data

Wilson Plot regression coefficient = 0.998
Ci (based on Petukhov-Popov)       = 2.499
Alpha (based on Nusselt)           = 0.945
Enhancement (constant heat flux)   = 1.218
Enhancement (constant temp drop)   = 1.159

                          Overall      Outside      Inside
                Coolant   Heat Xfer    Heat Xfer    Heat Xfer      Heat
               Velocity  Coefficient  Coefficient  Coefficient     Flux       Ts-Twall
Data   LMTD       Vw         Uo           Ho           Hi           Qp          Txf
  #   (degC)    (m/s)   (W/m^2-K)    (W/m^2-K)    (W/m^2-K)     (W/m^2)      (degC)

  1   31.48     4.18    6.911E+03    1.330E+04    3.913E+04    2.175E+05    16.35
  2   31.02     3.67    6.796E+03    1.343E+04    3.512E+04    2.108E+05    15.70
  3   30.87     3.16    6.676E+03    1.369E+04    3.101E+04    2.061E+05    15.06
  4   30.96     2.65    6.386E+03    1.346E+04    2.672E+04    1.977E+05    14.69
  5   30.74     2.14    6.139E+03    1.374E+04    2.237E+04    1.887E+05    13.74
  6   30.54     1.63    5.770E+03    1.406E+04    1.786E+04    1.762E+05    12.53
  7   30.20     1.12    5.261E+03    1.508E+04    1.313E+04    1.589E+05    10.54
  8   30.13     1.12    5.276E+03    1.520E+04    1.314E+04    1.590E+05    10.46
  9   30.45     1.63    5.737E+03    1.386E+04    1.787E+04    1.747E+05    12.60
 10   30.83     2.14    6.149E+03    1.379E+04    2.237E+04    1.895E+05    13.75
 11   30.84     2.65    6.395E+03    1.350E+04    2.673E+04    1.972E+05    14.61
 12   30.76     3.16    6.593E+03    1.333E+04    3.106E+04    2.028E+05    15.21
 13   30.85     3.67    6.732E+03    1.316E+04    3.523E+04    2.076E+05    15.78
 14   30.86     4.18    6.867E+03    1.311E+04    3.934E+04    2.119E+05    16.16
Avg                                  1.376E+04                 1.928E+05    14.08
```

```
          Program Name:                    DRPALL
          Raw data stored on file:         S48VZ
          Data taken by:                   INCHECK
          Tube type:                       RECTANGULAR FINNED TUBE
          Fin spacing, width, height:      1.50  1.00  0.48 (mm)
          Tube material:                   STAINLESS-STEEL
          Thermal conductivity:             14.3 (W/m-K)
          Inside diameter:                  13.11 (mm)
          Root diameter:                    14.26 (mm)
          Pressure condition:              VACUUM

             Room    Inlet   Outlet   Steam    Gage   Xducer
      Flow   Temp    Temp    Temp     Temp     Press  Press   Volts  Current
     (pct) (degC)  (degC)  (degC)   (degC)   (KPa)  (KPa)    (V)

  1   80   20.26   17.17   17.77    48.6     10.5   10.8    198.1   1.03
  2   70   20.26   17.37   18.03    48.7     10.5   11.0    198.9   1.03
  3   60   20.25   17.47   18.20    48.6     10.5   10.9    198.1   1.03
  4   50   20.31   17.33   18.17    48.6     10.6   10.9    198.0   1.03
  5   40   20.32   17.37   18.35    48.7     10.7   11.0    198.1   1.03
  6   30   20.30   17.49   18.69    48.7     10.7   11.0    198.3   1.03
  7   20   20.35   17.64   19.18    48.5     10.5   10.9    198.7   1.02
  8   20   20.37   17.66   19.21    48.6     10.7   11.0    198.2   1.03
  9   30   20.35   17.46   18.65    48.6     10.6   11.0    199.0   1.02
 10   40   20.37   17.41   18.39    48.7     10.6   11.0    197.6   1.03
 11   50   20.39   17.38   18.21    48.8     74.2   11.0    198.0   1.03
 12   60   20.40   17.41   18.14    48.6     10.6   10.9    197.9   1.03
 13   70   20.39   17.59   18.24    48.8     10.7   11.1    197.7   1.03
 14   80   20.39   17.59   18.19    48.7     10.7   11.0    198.0   1.03
```

```
          Program Name:                 DRPALL
          Raw data stored on file:      S48V2
          Data taken by:                INCHECK
          Tube type:                    RECTANGULAR FINNED TUBE
          Fin spacing, width, height:   1.50  1.00  0.48 (mm)
          Tube material:                STAINLESS-STEEL
          Thermal conductivity:          14.3 (W/m-K)
          Inside diameter:               13.11 (mm)
          Root diameter:                 14.26 (mm)
          Pressure condition:           VACUUM
          System power:                   6.82 (KW)
          Steam velocity:                 1.87 (m/s)
          This analysis includes end-fin effect
          HEATEX insert installed in tube
          Enhancements based on comparison to Incheck smooth tube data

          Wilson Plot regression coefficient = 0.899
          Ci (based on Petukhov-Popov)       = 2.501
          Alpha (based on Nusselt)           = 0.973
          Enhancement (constant heat flux)   = 1.267
          Enhancement (constant temp drop)   = 1.194

                            Overall     Outside     Inside
                   Coolant  Heat Xfer   Heat Xfer   Heat Xfer     Heat
                   Velocity Coefficient Coefficient Coefficient   Flux      Ts-Twall
Data   LMTD        Vw          Uo          Ho          Hi           Qp         Txf
 #    (degC)     (m/s)    (W/m^2-K)   (W/m^2-K)   (W/m^2-K)    (W/m^2)     (degC)

 1     31.18      4.18    7.001E+03   1.363E+04   3.918E+04   2.183E+05    16.01
 2     31.03      3.67    6.920E+03   1.391E+04   3.518E+04   2.147E+05    15.44
 3     30.80      3.16    6.738E+03   1.394E+04   3.105E+04   2.075E+05    14.89
 4     30.85      2.65    6.515E+03   1.404E+04   2.674E+04   2.010E+05    14.32
 5     30.85      2.14    6.234E+03   1.422E+04   2.237E+04   1.923E+05    13.52
 6     30.57      1.63    5.891E+03   1.480E+04   1.786E+04   1.801E+05    12.16
 7     30.12      1.12    5.301E+03   1.543E+04   1.312E+04   1.597E+05    10.35
 8     30.19      1.12    5.331E+03   1.567E+04   1.313E+04   1.609E+05    10.27
 9     30.52      1.63    5.853E+03   1.467E+04   1.785E+04   1.787E+05    12.26
10     30.81      2.14    6.260E+03   1.435E+04   2.238E+04   1.928E+05    13.43
11     30.97      2.65    6.471E+03   1.383E+04   2.675E+04   2.004E+05    14.49
12     30.83      3.16    6.733E+03   1.392E+04   3.102E+04   2.076E+05    14.91
13     30.94      3.67    6.892E+03   1.378E+04   3.527E+04   2.133E+05    15.47
14     30.84      4.18    6.987E+03   1.356E+04   3.937E+04   2.155E+05    15.90
Avg                                   1.428E+04               1.959E+05    13.82
```

```
        Program Name:                   DRPALL
        Raw data stored on file:        S75V1
        Data taken by:                  INCHECK
        Tube type:                      RECTANGULAR FINNED TUBE
        Fin spacing, width, height:     1.50  1.00  0.75 (mm)
        Tube material:                  STAINLESS-STEEL
        Thermal conductivity:            14.3 (W/m-K)
        Inside diameter:                 13.10 (mm)
        Root diameter:                   14.25 (mm)
        Pressure condition:             VACUUM

            Room    Inlet   Outlet   Steam    Gage    Xducer
      Flow  Temp    Temp    Temp     Temp     Press   Press   Volts   Current
     (pct) (degC)  (degC)  (degC)   (degC)   (KPa)   (KPa)    (V)

  1   80   20.52   18.81   19.35    48.5     10.7    10.8    198.1   1.04
  2   70   20.35   18.93   19.52    48.8     11.0    11.0    198.1   1.04
  3   60   21.47   19.07   19.73    48.7     11.0    11.0    198.2   1.04
  4   50   20.59   18.95   19.70    48.7     11.0    10.9    198.1   1.04
  5   40   21.30   19.09   19.97    48.7     11.0    10.9    197.6   1.04
  6   30   21.57   19.23   20.30    48.8     11.0    11.0    198.2   1.04
  7   20   21.61   19.36   20.75    48.6     10.9    10.9    198.3   1.04
  8   20   21.58   19.39   20.78    48.7     10.9    10.9    198.1   1.04
  9   30   21.02   19.14   20.21    48.7     10.9    10.9    198.0   1.04
 10   40   20.65   19.02   19.89    48.6     11.0    10.9    198.0   1.04
 11   50   20.54   18.95   19.70    48.6     10.9    10.9    198.2   1.04
 12   60   21.26   18.88   19.54    48.8     11.0    11.0    197.9   1.04
 13   70   21.36   19.05   19.64    48.7     11.0    11.0    197.9   1.04
 14   80   21.63   19.06   19.60    48.5     11.0    10.9    198.0   1.04
```

```
Program Name:                    DRPALL
Raw data stored on file:         S75U1
Data taken by:                   INCHECK
Tube type:                       RECTANGULAR FINNED TUBE
Fin spacing, width, height:      1.50  1.00  0.75 (mm)
Tube material:                   STAINLESS-STEEL
Thermal conductivity:             14.3 (W/m-K)
Inside diameter:                  13.10 (mm)
Root diameter:                    14.25 (mm)
Pressure condition:              VACUUM
System power:                      6.81 (KW)
Steam velocity:                    1.97 (m/s)
This analysis includes end-fin effect
HEATEX insert installed in tube
Enhancements based on comparison to Incheck smooth tube data

Wilson Plot regression coefficient = 1.000
Ci (based on Petukhov-Popov)       = 2.349
Alpha (based on Nusselt)           = 0.878
Enhancement (constant heat flux)   = 1.104
Enhancement (constant temp drop)   = 1.077

                         Overall      Outside       Inside
               Coolant  Heat Xfer    Heat Xfer     Heat Xfer       Heat
              Velocity Coefficient  Coefficient  Coefficient       Flux       Ts-Twall
Data   LMTD      Vw        Uo           Ho           Hi             Qp           Txf
  #   (degC)   (m/s)   (W/m^2-K)    (W/m^2-K)    (W/m^2-K)      (W/m^2)      (degC)

  1    29.47    4.19   6.606E+03    1.239E+04    3.755E+04    1.947E+05      15.71
  2    29.55    3.67   6.496E+03    1.251E+04    3.368E+04    1.920E+05      15.35
  3    29.32    3.16   6.364E+03    1.267E+04    2.973E+04    1.866E+05      14.72
  4    29.33    2.65   6.176E+03    1.284E+04    2.561E+04    1.811E+05      14.11
  5    29.15    2.14   5.907E+03    1.297E+04    2.145E+04    1.722E+05      13.28
  6    29.00    1.63   5.540E+03    1.320E+04    1.713E+04    1.607E+05      12.17
  7    28.54    1.12   5.052E+03    1.416E+04    1.258E+04    1.442E+05      10.18
  8    28.58    1.12   5.027E+03    1.396E+04    1.259E+04    1.437E+05      10.29
  9    28.98    1.63   5.559E+03    1.332E+04    1.711E+04    1.611E+05      12.09
 10    29.18    2.14   5.889E+03    1.289E+04    2.143E+04    1.718E+05      13.33
 11    29.26    2.65   6.136E+03    1.267E+04    2.561E+04    1.795E+05      14.17
 12    29.55    3.16   6.289E+03    1.239E+04    2.967E+04    1.859E+05      15.00
 13    29.40    3.67   6.471E+03    1.241E+04    3.373E+04    1.903E+05      15.33
 14    29.20    4.19   6.588E+03    1.232E+04    3.765E+04    1.924E+05      15.62
Avg                                 1.291E+04                 1.754E+05      13.67
```

```
          Program Name:                    DRPALL
          Raw data stored on file:         S75V2
          Data taken by:                   INCHECK
          Tube type:                       RECTANGULAR FINNED TUBE
          Fin spacing, width, height:      1.50  1.00  0.75 (mm)
          Tube material:                   STAINLESS-STEEL
          Thermal conductivity:             14.3 (W/m-K)
          Inside diameter:                  13.10 (mm)
          Root diameter:                    14.25 (mm)
          Pressure condition:              VACUUM

             Room    Inlet   Outlet   Steam    Gage    Xducer
      Flow   Temp    Temp    Temp     Temp     Press   Press    Volts   Current
     (pct) (degC)  (degC)  (degC)   (degC)   (KPa)   (KPa)     (V)

  1   80   20.90   18.88   19.40    48.6     11.0    10.9    197.9    1.04
  2   70   20.95   18.89   19.46    48.8     11.2    10.9    197.8    1.04
  3   60   21.00   18.91   19.55    48.8     11.1    11.0    198.0    1.04
  4   50   21.02   18.96   19.68    48.8     11.0    11.0    198.0    1.04
  5   40   21.02   18.72   19.57    48.7     11.0    10.9    198.1    1.04
  6   30   21.12   18.77   19.80    48.8     11.0    10.9    198.2    1.04
  7   20   21.12   18.88   20.22    48.7     11.0    11.0    198.0    1.04
  8   20   21.12   18.87   20.21    48.7     11.0    11.0    198.0    1.04
  9   30   21.15   18.63   19.66    48.7     11.0    11.0    198.1    1.04
 10   40   21.14   18.46   19.31    48.8     11.0    11.0    198.1    1.03
 11   50   21.15   18.39   19.12    48.8     11.0    11.0    198.3    1.03
 12   60   21.14   18.34   18.98    48.8     11.0    11.0    198.1    1.03
 13   70   21.16   18.48   19.06    48.7     11.0    10.9    197.9    1.03
 14   80   21.23   18.46   18.98    48.8     11.0    11.0    197.9    1.03
```

```
Program Name:                   DRPALL
Raw data stored on file:        S75V2
Data taken by:                  INCHECK
Tube type:                      RECTANGULAR FINNED TUBE
Fin spacing, width, height:     1.50  1.00  0.75 (mm)
Tube material:                  STAINLESS-STEEL
Thermal conductivity:           14.3 (W/m-K)
Inside diameter:                 13.10 (mm)
Root diameter:                   14.25 (mm)
Pressure condition:             VACUUM
System power:                     6.81 (KW)
Steam velocity:                   1.96 (m/s)
This analysis includes end-fin effect
HEATEX insert installed in tube
Enhancements based on comparison to Incheck smooth tube data

Wilson Plot regression coefficient = 0.998
Ci (based on Petukhov-Popov)       = 3.170
Alpha (based on Nusselt)           = 0.839
Enhancement (constant heat flux)   = 1.039
Enhancement (constant temp drop)   = 1.029

                         Overall     Outside      Inside
               Coolant  Heat Xfer   Heat Xfer    Heat Xfer      Heat
              Velocity Coefficient Coefficient Coefficient      Flux      Ts-Twall
Data   LMTD      Vw         Uo          Ho          Hi           Qp          Txf
 #   (degC)    (m/s)   (W/m^2-K)   (W/m^2-K)   (W/m^2-K)     (W/m^2)      (degC)

  1   29.49    4.19    6.329E+03   1.177E+04   3.471E+04    1.866E+05    15.86
  2   29.59    3.67    6.245E+03   1.197E+04   3.110E+04    1.848E+05    15.43
  3   29.55    3.16    6.098E+03   1.209E+04   2.742E+04    1.802E+05    14.91
  4   29.49    2.65    5.880E+03   1.211E+04   2.366E+04    1.734E+05    14.32
  5   29.56    2.14    5.662E+03   1.249E+04   1.973E+04    1.674E+05    13.41
  6   29.47    1.63    5.269E+03   1.258E+04   1.574E+04    1.553E+05    12.35
  7   29.17    1.12    4.773E+03   1.339E+04   1.156E+04    1.392E+05    10.40
  8   29.16    1.12    4.770E+03   1.337E+04   1.156E+04    1.391E+05    10.40
  9   29.55    1.63    5.268E+03   1.259E+04   1.571E+04    1.557E+05    12.36
 10   29.87    2.14    5.573E+03   1.208E+04   1.967E+04    1.664E+05    13.78
 11   30.01    2.65    5.855E+03   1.204E+04   2.351E+04    1.757E+05    14.59
 12   30.12    3.15    6.035E+03   1.188E+04   2.724E+04    1.817E+05    15.30
 13   29.98    3.57    6.170E+03   1.173E+04   3.096E+04    1.950E+05    15.78
 14   30.06    4.19    6.271E+03   1.159E+04   3.455E+04    1.985E+05    16.27
Avg                                1.226E+04                1.699E+05    13.94
```

```
             Program Name:                  ORPALL
             Raw data stored on file:       S95V1
             Data taken by:                 INCHECK
             Tube type:                     RECTANGULAR FINNED TUBE
             Fin spacing, width, height:    1.50  1.00  0.95 (mm)
             Tube material:                 STAINLESS-STEEL
             Thermal conductivity:           14.3 (W/m-K)
             Inside diameter:                13.08 (mm)
             Root diameter:                  14.24 (mm)
             Pressure condition:            VACUUM

             Room    Inlet   Outlet   Steam    Gage   Xducer
      Flow   Temp    Temp    Temp     Temp     Press  Press    Volts   Current
     (pct) (degC)  (degC)  (degC)   (degC)   (KPa)  (KPa)     (V)

  1   80   22.38   19.19   19.68    48.6     10.8   10.8    198.0    1.04
  2   70   22.56   19.32   19.86    48.8     10.8   10.9    198.1    1.04
  3   60   21.94   19.49   20.08    48.6     10.8   10.8    197.9    1.04
  4   50   21.78   19.40   20.08    48.9     11.0   11.0    198.0    1.04
  5   40   21.69   19.58   20.36    48.6     10.8   10.8    198.0    1.04
  6   30   22.49   19.66   20.62    48.8     10.8   10.9    197.8    1.04
  7   20   22.57   19.84   21.09    48.8     10.8   10.9    198.0    1.04
  8   20   22.51   19.82   21.06    48.8     10.8   11.0    198.0    1.04
  9   30   22.54   19.67   20.63    48.9     10.9   11.0    197.8    1.04
 10   40   22.49   19.63   20.41    48.5     10.7   10.8    198.0    1.04
 11   50   22.76   19.70   20.36    48.6     10.8   10.9    197.9    1.04
 12   60   22.73   19.87   20.45    48.8     11.0   10.9    197.9    1.04
 13   70   22.68   19.86   20.38    48.7     11.0   10.9    198.1    1.04
 14   80   22.63   19.86   20.34    48.7     10.8   10.9    198.1    1.04
```

```
Program Name:                    DRPALL
Raw data stored on file:         SS5V1
Data taken by:                   INCHECK
Tube type:                       RECTANGULAR FINNED TUBE
Fin spacing, width, height:      1.50  1.00  0.95 (mm)
Tube material:                   STAINLESS-STEEL
Thermal conductivity:             14.3 (W/m-K)
Inside diameter:                  13.08 (mm)
Root diameter:                    14.24 (mm)
Pressure condition:              VACUUM
System power:                      6.80 (KW)
Steam velocity:                    1.96 (m/s)
This analysis includes end-fin effect
HEATEX insert installed in tube
Enhancements based on comparison to Incheck smooth tube data

Wilson Plot regression coefficient = 0.999
Ci (based on Petukhov-Popov)       = 2.100
Alpha (based on Nusselt)           = 0.772
Enhancement (constant heat flux)   = 0.930
Enhancement (constant temp drop)   = 0.947

                       Overall     Outside     Inside
              Coolant  Heat Xfer   Heat Xfer   Heat Xfer      Heat
             Velocity Coefficient Coefficient Coefficient     Flux       Ts-Twall
Data   LMTD     Vw        Uo          Ho          Hi           Qp          Txf
  #  (degC)  (m/s)   (W/m^2-K)   (W/m^2-K)   (W/m^2-K)     (W/m^2)      (degC)

  1   29.18   4.20   6.021E+03   1.089E+04   3.380E+04   1.757E+05    16.13
  2   29.18   3.69   5.900E+03   1.092E+04   3.033E+04   1.722E+05    15.77
  3   28.86   3.17   5.785E+03   1.108E+04   3.678E+04   1.670E+05    15.07
  4   29.13   2.66   5.632E+03   1.130E+04   2.307E+04   1.640E+05    14.52
  5   28.63   2.15   5.369E+03   1.134E+04   1.933E+04   1.537E+05    13.56
  6   28.65   1.64   5.053E+03   1.165E+04   1.542E+04   1.448E+05    12.42
  7   28.33   1.13   4.584E+03   1.234E+04   1.134E+04   1.299E+05    10.53
  8   28.35   1.13   4.542E+03   1.204E+04   1.133E+04   1.288E+05    10.69
  9   28.77   1.64   5.048E+03   1.163E+04   1.543E+04   1.452E+05    12.49
 10   28.49   2.15   5.373E+03   1.135E+04   1.934E+04   1.531E+05    13.49
 11   28.91   2.66   5.578E+03   1.106E+04   2.315E+04   1.596E+05    14.42
 12   28.65   3.17   5.751E+03   1.094E+04   2.689E+04   1.648E+05    15.07
 13   28.64   3.69   5.846E+03   1.071E+04   3.051E+04   1.674E+05    15.63
 14   28.61   4.20   5.935E+03   1.059E+04   3.406E+04   1.598E+05    16.04
Avg                              1.127E+04               1.569E+05    13.99
```

```
Program Name:                   DRPALL
Raw data stored on file:        S95V2
Data taken by:                  INCHECK
Tube type:                      RECTANGULAR FINNED TUBE
Fin spacing, width, height:     1.50  1.00  0.95 (mm)
Tube material:                  STAINLESS-STEEL
Thermal conductivity:            14.3 (W/m-K)
Inside diameter:                 13.08 (mm)
Root diameter:                   14.24 (mm)
Pressure condition:             VACUUM

            Room    Inlet   Outlet    Steam     Gage   Xducer
     Flow   Temp    Temp    Temp      Temp     Press   Press    Volts   Current
    (pct) (degC)  (degC)  (degC)    (degC)    (KPa)   (KPa)     (V)

  1   80   21.97   19.06   19.58     48.7     11.4     11.3    197.6    1.03
  2   70   21.95   19.21   19.77     48.7     11.4     11.4    198.0    1.04
  3   60   21.97   19.32   19.94     48.7     11.4     11.3    197.9    1.04
  4   50   21.67   19.20   19.92     48.7     11.4     11.3    197.9    1.04
  5   40   21.51   19.28   20.11     48.7     11.3     11.4    198.1    1.04
  6   30   21.43   19.35   20.36     48.7     11.4     11.3    198.0    1.04
  7   20   21.47   19.54   20.85     48.6     11.4     11.3    197.9    1.04
  8   20   21.41   19.47   20.79     48.7     11.4     11.3    197.8    1.04
  9   30   21.25   19.28   20.30     48.6     11.3     11.3    198.0    1.04
 10   40   21.38   19.17   20.01     48.8     11.4     11.4    198.1    1.04
 11   50   21.33   19.11   19.82     48.7     11.4     11.3    198.3    1.04
 12   60   21.36   19.06   19.58     48.5     11.3     11.3    198.1    1.04
 13   70   21.33   19.20   19.77     48.7     11.4     11.3    198.0    1.04
 14   80   21.43   19.19   19.71     48.7     11.3     11.4    198.3    1.04
```

```
Program Name:                  DRPALL
Raw data stored on file:       S95V2
Data taken by:                 INCHECK
Tube type:                     RECTANGULAR FINNED TUBE
Fin spacing, width, height:    1.50  1.00  0.95 (mm)
Tube material:                 STAINLESS-STEEL
Thermal conductivity:           14.3 (W/m-K)
Inside diameter:                13.08 (mm)
Root diameter:                  14.24 (mm)
Pressure condition:            VACUUM
System power:                   6.81 (KW)
Steam velocity:                  1.97 (m/s)
This analysis includes end-fin effect
HEATEX insert installed in tube
Enhancements based on comparison to Incheck smooth tube data

Wilson Plot regression coefficient = 1.000
Ci (based on Petukhov-Popov)       = 2.208
Alpha (based on Nusselt)           = 0.932
Enhancement (constant heat flux)   = 1.028
Enhancement (constant temp drop)   = 1.021

                       Overall     Outside     Inside
            Coolant   Heat Xfer   Heat Xfer   Heat Xfer      Heat
           Velocity Coefficient Coefficient Coefficient      Flux       Ts-Twall
Date  LMTD     Vw         Uo          Ho          Hi           Qp          Txf
 #   (degC)  (m/s)   (W/m^2-K)   (W/m^2-K)   (W/m^2-K)     (W/m^2)      (degC)

 1   29.41   4.20   6.300E+03   1.163E+04   3.549E+04   1.853E+05    15.93
 2   29.25   3.69   6.194E+03   1.174E+04   3.184E+04   1.813E+05    15.44
 3   29.07   3.17   6.087E+03   1.197E+04   2.810E+04   1.769E+05    14.79
 4   29.11   2.66   5.915E+03   1.217E+04   2.421E+04   1.722E+05    14.15
 5   29.04   2.15   5.642E+03   1.224E+04   2.026E+04   1.638E+05    13.39
 6   28.84   1.64   5.301E+03   1.255E+04   1.618E+04   1.529E+05    12.19
 7   28.41   1.13   4.808E+03   1.330E+04   1.188E+04   1.366E+05    10.27
 8   28.55   1.13   4.799E+03   1.324E+04   1.187E+04   1.370E+05    10.35
 9   28.85   1.64   5.307E+03   1.259E+04   1.615E+04   1.531E+05    12.16
10   29.18   2.15   5.662E+03   1.234E+04   2.023E+04   1.652E+05    13.39
11   29.19   2.66   5.862E+03   1.195E+04   2.418E+04   1.711E+05    14.32
12   29.17   3.17   6.068E+03   1.191E+04   2.802E+04   1.770E+05    14.86
13   29.19   3.69   6.203E+03   1.177E+04   3.184E+04   1.811E+05    15.39
14   29.28   4.20   6.297E+03   1.162E+04   3.654E+04   1.844E+05    15.87
Avg                             1.221E+04               1.670E+05    13.75
```

```
          Program Name:                DRPALL
          Raw data stored on file:     S126V1
          Data taken by:               INCHECK
          Tube type:                   RECTANGULAR FINNED TUBE
          Fin spacing, width, height:  1.50  1.00  1.26 (mm)
          Tube material:               STAINLESS-STEEL
          Thermal conductivity:         14.3 (W/m-K)
          Inside diameter:              13.08 (mm)
          Root diameter:                14.21 (mm)
          Pressure condition:          VACUUM

            Room     Inlet   Outlet   Steam    Gage    Xducer
      Flow  Temp     Temp    Temp     Temp     Press   Press    Volts   Current
     (pct) (degC)   (degC)  (degC)   (degC)   (KPa)   (KPa)     (V)

  1   80   21.50    20.38   20.85    48.7     10.5    10.9    197.9    1.04
  2   70   21.38    20.42   20.92    48.6     10.3    10.9    198.0    1.04
  3   60   21.96    20.48   21.04    48.6     10.4    10.8    198.1    1.03
  4   50   21.65    20.29   20.93    48.8     10.9    11.0    198.1    1.04
  5   40   21.58    20.31   21.06    48.9     11.0    11.0    198.0    1.04
  6   30   21.82    20.32   21.23    48.8     76.1    11.0    198.2    1.03
  7   20   21.87    20.45   21.64    48.8     11.0    11.0    197.6    1.03
  8   20   21.92    20.42   21.62    48.8     10.8    11.0    197.9    1.03
  9   30   21.95    20.11   21.03    48.7     10.9    10.9    198.0    1.04
 10   40   21.93    19.98   20.74    48.8     11.0    10.9    197.7    1.03
 11   50   22.03    19.91   20.56    48.7     10.9    10.9    197.9    1.04
 12   60   22.15    20.09   20.66    48.8     10.9    10.9    197.7    1.04
 13   70   22.13    20.06   20.57    48.8     10.9    10.9    197.6    1.04
 14   80   22.12    20.06   20.53    48.8     10.9    10.9    198.1    1.04
```

```
Program Name:                  DRPALL
Raw data stored on file:       S126V1
Data taken by:                 INCHECK
Tube type:                     RECTANGULAR FINNED TUBE
Fin spacing, width, height:    1.50  1.00  1.26 (mm)
Tube material:                 STAINLESS-STEEL
Thermal conductivity:           14.3 (W/m-K)
Inside diameter:                13.08 (mm)
Root diameter:                  14.21 (mm)
Pressure condition:            VACUUM
System power:                    6.80 (KW)
Steam velocity:                  1.96 (m/s)
This analysis includes end-fin effect
HEATEX insert installed in tube
Enhancements based on comparison to Incheck smooth tube data

Wilson Plot regression coefficient = 0.999
Ci (based on Petukhov-Popov)       = 2.006
Alpha (based on Nusselt)           = 0.746
Enhancement (constant heat flux)   = 0.888
Enhancement (constant temp drop)   = 0.815

                          Overall     Outside      Inside
              Coolant   Heat Xfer   Heat Xfer    Heat Xfer      Heat
              Velocity Coefficient Coefficient Coefficient      Flux      Ts-Twall
 Data   LMTD     Vw        Uo          Ho           Hi           Qp          Txf
   #  (degC)   (m/s)   (W/m^2-K)   (W/m^2-K)    (W/m^2-K)     (W/m^2)     (degC)

   1   28.11   4.20    5.946E+03   1.063E+04    3.271E+04    1.671E+05    15.72
   2   27.95   3.69    5.807E+03   1.061E+04    2.831E+04    1.623E+05    15.30
   3   27.82   3.17    5.685E+03   1.075E+04    2.586E+04    1.591E+05    14.72
   4   28.20   2.66    5.483E+03   1.077E+04    2.226E+04    1.546E+05    14.36
   5   28.20   2.15    5.225E+03   1.082E+04    1.861E+04    1.474E+05    13.62
   6   28.05   1.64    4.908E+03   1.109E+04    1.484E+04    1.377E+05    12.42
   7   27.78   1.13    4.475E+03   1.192E+04    1.090E+04    1.243E+05    10.43
   8   27.77   1.13    4.489E+03   1.202E+04    1.089E+04    1.246E+05    10.37
   9   28.17   1.64    4.923E+03   1.118E+04    1.480E+04    1.387E+05    12.40
  10   28.40   2.15    5.247E+03   1.094E+04    1.854E+04    1.490E+05    13.62
  11   28.51   2.66    5.463E+03   1.072E+04    2.216E+04    1.557E+05    14.53
  12   28.41   3.17    5.655E+03   1.066E+04    2.575E+04    1.606E+05    15.07
  13   28.47   3.69    5.774E+03   1.051E+04    2.920E+04    1.644E+05    15.64
  14   28.49   4.20    5.853E+03   1.035E+04    3.260E+04    1.668E+05    16.11
 Avg                               1.093E+04                 1.508E+05    13.88
```

```
Program Name:                   DRPALL
Raw data stored on file:        S126V2
Data taken by:                  INCHECK
Tube type:                      RECTANGULAR FINNED TUBE
Fin spacing, width, height:     1.50  1.00  1.25 (mm)
Tube material:                  STAINLESS-STEEL
Thermal conductivity:            14.3 (W/m-K)
Inside diameter:                 13.08 (mm)
Root diameter:                   14.21 (mm)
Pressure condition:             VACUUM

             Room    Inlet   Outlet   Steam    Gage    Xducer
      Flow   Temp    Temp    Temp     Temp     Press   Press    Volts  Current
     (pct) (degC)  (degC)  (degC)   (degC)   (KPa)   (KPa)    (V)

 1    80   22.98   19.71   20.20    48.8     10.5    11.0    198.1    1.04
 2    70   23.06   19.86   20.38    48.8     10.5    10.9    198.1    1.04
 3    60   22.95   19.96   20.54    48.7     10.4    10.8    197.8    1.04
 4    50   23.12   19.86   20.51    48.6     10.5    10.9    198.1    1.04
 5    40   22.98   19.89   20.66    48.8     10.5    10.9    198.1    1.04
 6    30   23.15   19.98   20.92    48.9     10.5    11.0    197.7    1.04
 7    20   23.04   20.15   21.38    48.8     10.5    11.0    198.0    1.04
 8    20   23.14   20.13   21.36    48.8     10.5    11.0    197.9    1.04
 9    30   23.21   19.90   20.84    48.7     10.5    10.9    197.9    1.04
10    40   22.08   19.81   20.58    48.7     10.5    10.9    198.0    1.04
11    50   22.15   19.74   20.40    48.6     10.5    10.9    197.8    1.04
12    60   22.08   19.93   20.51    48.6     10.5    10.9    198.3    1.04
13    70   21.29   19.94   20.46    48.6     10.5    10.9    198.1    1.04
14    80   21.23   19.95   20.43    48.6     10.5    10.9    198.1    1.04
```

```
Program Name:                     DRPALL
Raw data stored on file:          8126U2
Data taken by:                    INCHECK
Tube type:                        RECTANGULAR FINNED TUBE
Fin spacing, width, height:       1.50  1.00  1.26 (mm)
Tube material:                    STAINLESS-STEEL
Thermal conductivity:              14.3 (W/m-K)
Inside diameter:                   13.08 (mm)
Root diameter:                     14.21 (mm)
Pressure condition:               VACUUM
System power:                      6.81 (KW)
Steam velocity:                     1.96 (m/s)
This analysis includes end-fin effect
HEATEX insert installed in tube
Enhancements based on comparison to Incheck smooth tube data

Wilson Plot regression coefficient = 1.000
Ci (based on Petukhov-Popov)       = 2.085
Alpha (based on Nusselt)           = 0.760
Enhancement (constant heat flux)   = 0.812
Enhancement (constant temp drop)   = 0.933

                      Overall      Outside      Inside
             Coolant  Heat Xfer    Heat Xfer    Heat Xfer      Heat
            Velocity Coefficient Coefficient Coefficient       Flux       Ts-Twall
 Data   LMTD     Vw       Uo           Ho           Hi           Qp          Txf
   #   (degC)  (m/s)  (W/m^2-K)    (W/m^2-K)    (W/m^2-K)     (W/m^2)      (degC)

   1    28.91   4.20   5.982E+03    1.064E+04    3.372E+04    1.729E+05    16.26
   2    28.65   3.69   5.903E+03    1.080E+04    3.025E+04    1.691E+05    15.66
   3    28.42   3.17   5.745E+03    1.080E+04    2.670E+04    1.633E+05    15.11
   4    28.46   2.66   5.574E+03    1.094E+04    2.300E+04    1.586E+05    14.50
   5    28.50   2.15   5.341E+03    1.110E+04    1.924E+04    1.522E+05    13.72
   6    28.45   1.64   5.026E+03    1.139E+04    1.535E+04    1.430E+05    12.55
   7    28.03   1.13   4.563E+03    1.206E+04    1.128E+04    1.279E+05    10.60
   8    28.02   1.13   4.571E+03    1.213E+04    1.128E+04    1.281E+05    10.56
   9    28.31   1.64   5.030E+03    1.142E+04    1.534E+04    1.424E+05    12.47
  10    28.48   2.15   5.322E+03    1.102E+04    1.922E+04    1.516E+05    13.76
  11    28.53   2.66   5.584E+03    1.098E+04    2.297E+04    1.593E+05    14.50
  12    28.44   3.17   5.747E+03    1.082E+04    2.669E+04    1.635E+05    15.11
  13    28.45   3.69   5.880E+03    1.072E+04    3.028E+04    1.673E+05    15.61
  14    28.47   4.20   5.975E+03    1.061E+04    3.380E+04    1.701E+05    16.04
 Avg                                1.110E+04                 1.550E+05    14.03
```

```
Program Name:                   DRPALL
Raw data stored on file:        S142V3
Data taken by:                  INCHECK
Tube type:                      RECTANGULAR FINNED TUBE
Fin spacing, width, height:     1.50  1.00  1.42 (mm)
Tube material:                  STAINLESS-STEEL
Thermal conductivity:            14.3 (W/m-K)
Inside diameter:                 13.10 (mm)
Root diameter:                   14.28 (mm)
Pressure condition:             VACUUM

          Room    Inlet   Outlet   Steam    Gage    Xducer
   Flow   Temp    Temp    Temp     Temp     Press   Press    Volts   Current
  (pct) (degC)  (degC)  (degC)   (degC)   (KPa)   (KPa)     (V)

 1   80   20.29   17.39   17.87    48.6     10.9    10.9    198.0    1.03
 2   70   20.32   17.48   18.00    48.7     11.0    10.9    198.0    1.03
 3   60   20.28   17.53   18.11    48.7     11.0    10.9    198.0    1.03
 4   50   20.34   17.39   18.07    48.7     11.0    11.0    197.9    1.03
 5   40   20.31   17.43   18.22    48.6     10.9    10.9    198.1    1.03
 6   30   20.26   17.48   18.45    48.7     10.8    10.9    198.2    1.03
 7   20   20.35   17.63   18.88    48.6     10.9    10.8    198.1    1.03
 8   20   20.30   17.62   18.88    48.5     10.8    10.8    198.3    1.03
 9   30   20.31   17.36   18.33    48.5     10.7    10.8    198.6    1.03
10   40   20.34   17.24   18.04    48.6     10.8    10.9    198.0    1.03
11   50   20.35   17.16   17.83    48.7     10.9    10.9    197.7    1.03
12   60   20.34   17.10   17.89    48.6     10.8    10.9    197.7    1.03
13   70   20.32   17.23   17.76    48.6     10.8    10.9    198.0    1.03
14   80   20.34   17.24   17.72    48.8     10.9    10.9    198.2    1.03
```

```
Program Name:                   DRPALL
Raw data stored on file:        S142V3
Data taken by:                  INCHECK
Tube type:                      RECTANGULAR FINNED TUBE
Fin spacing, width, height:     1.50  1.00  1.42 (mm)
Tube material:                  STAINLESS-STEEL
Thermal conductivity:            14.3 (W/m-K)
Inside diameter:                 13.10 (mm)
Root diameter:                   14.28 (mm)
Pressure condition:             VACUUM
System power:                     6.81 (KW)
Steam velocity:                   1.97 (m/s)
This analysis includes end-fin effect
HEATEX insert installed in tube
Enhancements based on comparison to Incheck smooth tube data

Wilson Plot regression coefficient = 1.000
Ci (based on Petukhov-Popov)       = 2.136
Alpha (based on Nusselt)           = 0.708
Enhancement (constant heat flux)   = 0.829
Enhancement (constant temp drop)   = 0.869

                         Overall     Outside     Inside
              Coolant   Heat Xfer   Heat Xfer   Heat Xfer      Heat
             Velocity Coefficient Coefficient Coefficient     Flux       Ts-Twall
 Data   LMTD     Vw        Uo          Ho          Hi          Qp          Txf
  #   (degC)   (m/s)   (W/m^2-K)   (W/m^2-K)   (W/m^2-K)    (W/m^2)      (degC)

  1    31.03   4.19   5.509E+03   9.413E+03   3.358E+04   1.709E+05    18.16
  2    30.93   3.67   5.462E+03   9.607E+03   3.011E+04   1.690E+05    17.59
  3    30.87   3.16   5.342E+03   9.667E+03   2.655E+04   1.649E+05    17.06
  4    31.01   2.65   5.222E+03   9.882E+03   2.286E+04   1.619E+05    16.38
  5    30.78   2.14   4.991E+03   9.915E+03   1.912E+04   1.536E+05    15.49
  6    30.69   1.63   4.740E+03   1.028E+04   1.525E+04   1.455E+05    14.15
  7    30.30   1.12   4.296E+03   1.067E+04   1.121E+04   1.302E+05    12.20
  8    30.32   1.12   4.305E+03   1.073E+04   1.121E+04   1.305E+05    12.17
  9    30.74   1.63   4.743E+03   1.031E+04   1.523E+04   1.458E+05    14.14
 10    30.99   2.14   5.015E+03   1.002E+04   1.908E+04   1.554E+05    15.51
 11    31.19   2.65   5.193E+03   9.790E+03   2.280E+04   1.620E+05    16.54
 12    31.17   3.16   5.349E+03   9.710E+03   2.642E+04   1.667E+05    17.17
 13    31.14   3.67   5.435E+03   9.531E+03   3.002E+04   1.693E+05    17.76
 14    31.31   4.19   5.534E+03   9.490E+03   3.352E+04   1.733E+05    18.26
Avg                               9.930E+03               1.571E+05    15.90
```

```
          Program Name:                   DRPALL
          Raw data stored on file:        S142V4
          Data taken by:                  INCHECK
          Tube type:                      RECTANGULAR FINNED TUBE
          Fin spacing, width, height:     1.50  1.00  1.42 (mm)
          Tube material:                  STAINLESS-STEEL
          Thermal conductivity:            14.3 (W/m-K)
          Inside diameter:                 13.10 (mm)
          Root diameter:                   14.28 (mm)
          Pressure condition:             VACUUM

              Room    Inlet   Outlet   Steam    Gage   Xducer
       Flow   Temp    Temp    Temp     Temp     Press  Press   Volts  Current
      (pct) (degC)  (degC)  (degC)   (degC)   (KPa)  (KPa)    (V)

  1    80    19.81   17.24   17.73    48.8    11.0    10.9   198.0   1.04
  2    70    19.83   17.30   17.83    48.8    11.0    10.9   198.0   1.04
  3    60    19.86   17.35   17.94    48.7    11.0    10.8   197.9   1.04
  4    50    19.86   17.17   17.85    48.6    11.0    10.8   198.0   1.03
  5    40    19.85   17.19   18.00    48.7    11.0    10.9   198.2   1.03
  6    30    19.85   17.22   18.20    48.7    11.0    10.9   198.0   1.03
  7    20    19.85   17.38   18.65    48.7    11.0    10.9   198.0   1.04
  8    20    19.74   17.46   18.73    48.7    11.0    10.8   197.9   1.04
  9    30    19.74   17.14   18.11    48.6    11.0    10.8   197.9   1.04
 10    40    19.75   17.03   17.83    48.6    11.0    10.8   198.0   1.04
 11    50    19.73   16.95   17.63    48.7    11.0    10.8   198.1   1.04
 12    60    19.77   16.92   17.52    48.7    10.9    10.9   198.0   1.04
 13    70    19.76   17.06   17.60    48.7    11.0    10.8   198.0   1.04
 14    80    19.75   17.05   17.55    48.7    11.0    10.9   198.1   1.04
```

```
Program Name:                   DRPALL
Raw data stored on file:        S142V4
Data taken by:                  INCHECK
Tube type:                      RECTANGULAR FINNED TUBE
Fin spacing, width, height:     1.50  1.00  1.42 (mm)
Tube material:                  STAINLESS-STEEL
Thermal conductivity:            14.3 (W/m-K)
Inside diameter:                 13.10 (mm)
Root diameter:                   14.28 (mm)
Pressure condition:             VACUUM
System power:                     6.81 (KW)
Steam velocity:                   1.96 (m/s)
This analysis includes end-fin effect
HEATEX insert installed in tube
Enhancements based on comparison to Incheck smooth tube data

Wilson Plot regression coefficient = 0.999
Ci (based on Petukhov-Popov)       = 2.066
Alpha (based on Nusselt)           = 0.725
Enhancement (constant heat flux)   = 0.856
Enhancement (constant temp drop)   = 0.890

                          Overall      Outside      Inside
               Coolant   Heat Xfer    Heat Xfer    Heat Xfer      Heat
               Velocity Coefficient  Coefficient  Coefficient     Flux        Ts-Twall
Data   LMTD       Vw         Uo           Ho           Hi          Qp           Txf
 #    (degC)    (m/s)   (W/m^2-K)    (W/m^2-K)    (W/m^2-K)     (W/m^2)      (degC)

 1    31.35     4.19    5.547E+03    9.629E+03    3.242E+04    1.739E+05     18.06
 2    31.25     3.67    5.497E+03    9.836E+03    2.906E+04    1.718E+05     17.46
 3    31.07     3.16    5.368E+03    9.893E+03    2.563E+04    1.658E+05     16.86
 4    31.14     2.65    5.250E+03    1.016E+04    2.206E+04    1.635E+05     16.10
 5    31.10     2.14    5.059E+03    1.040E+04    1.845E+04    1.573E+05     15.12
 6    30.96     1.63    4.723E+03    1.046E+04    1.471E+04    1.462E+05     13.95
 7    30.71     1.12    4.299E+03    1.111E+04    1.081E+04    1.320E+05     11.89
 8    30.61     1.12    4.291E+03    1.104E+04    1.082E+04    1.313E+05     11.90
 9    31.00     1.63    4.724E+03    1.049E+04    1.470E+04    1.464E+05     13.96
10    31.21     2.14    5.043E+03    1.036E+04    1.841E+04    1.574E+05     15.21
11    31.40     2.65    5.208E+03    1.001E+04    2.200E+04    1.636E+05     16.33
12    31.49     3.16    5.370E+03    9.921E+03    2.550E+04    1.691E+05     17.04
13    31.41     3.67    5.560E+03    1.005E+04    2.898E+04    1.746E+05     17.38
14    31.39     4.19    5.567E+03    9.695E+03    3.230E+04    1.748E+05     18.03
Avg                                  1.022E+04                 1.592E+05     15.66
```

```
        Program Name:                   ORPALL
        Raw data stored on file:        S142V5
        Data taken by:                  INCHECK
        Tube type:                      RECTANGULAR FINNED TUBE
        Fin spacing, width, height:     1.50  1.00  1.42 (mm)
        Tube material:                  STAINLESS-STEEL
        Thermal conductivity:            14.3 (W/m-K)
        Inside diameter:                 13.10 (mm)
        Root diameter:                   14.28 (mm)
        Pressure condition:             VACUUM

               Room    Inlet   Outlet   Steam    Gage   Xducer
        Flow   Temp    Temp    Temp     Temp     Press  Press    Volts   Current
       (pct) (degC)  (degC)  (degC)   (degC)   (KPa)  (KPa)     (V)

  1     80   19.55   18.13   18.61    48.9     10.3   11.0     197.9   1.04
  2     70   19.56   18.03   18.54    48.6     10.8   10.9     198.0   1.02
  3     60   19.57   17.98   18.56    48.7     10.6   10.9     198.0   1.03
  4     50   19.59   17.74   18.41    48.7     10.8   10.9     198.1   1.03
  5     40   19.60   17.55   18.44    48.6     10.8   10.9     198.1   1.04
  6     30   19.62   17.63   18.58    48.9     10.6   10.8     198.1   1.03
  7     20   19.61   17.62   18.89    48.9     10.9   10.9     198.2   1.03
  8     20   19.63   17.55   18.81    48.8     10.8   10.9     198.0   1.03
  9     30   19.63   17.48   18.45    48.6     10.8   10.9     197.9   1.03
 10     40   19.64   17.18   17.96    48.7     10.5   10.9     198.2   1.03
 11     50   19.64   17.17   17.85    48.7     10.8   10.9     198.0   1.03
 12     60   19.63   17.11   17.71    48.7     10.8   11.0     198.0   1.03
 13     70   19.63   17.25   17.79    48.6     10.7   10.8     198.0   1.03
 14     80   19.63   17.23   17.72    48.6     10.5   10.9     198.1   1.03
```

```
Program Name:                  DRPALL
Raw data stored on file:       S142V5
Data taken by:                 INCHECK
Tube type:                     RECTANGULAR FINNED TUBE
Fin spacing, width, height:    1.50  1.00  1.42 (mm)
Tube material:                 STAINLESS-STEEL
Thermal conductivity:           14.3 (W/m-K)
Inside diameter:                13.10 (mm)
Root diameter:                  14.28 (mm)
Pressure condition:            VACUUM
System power:                   6.81 (KW)
Steam velocity:                  1.97 (m/s)
This analysis includes end-fin effect
HEATEX insert installed in tube
Enhancements based on comparison to Incheck smooth tube data

Wilson Plot regression coefficient = 0.997
Ci (based on Petukhov-Popov)       = 3.112
Alpha (based on Nusselt)           = 0.712
Enhancement (constant heat flux)   = 0.835
Enhancement (constant temp drop)   = 0.874

                          Overall     Outside     Inside
              Coolant    Heat Xfer   Heat Xfer   Heat Xfer     Heat
              Velocity  Coefficient Coefficient Coefficient    Flux      Ts-Twall
Data   LMTD     Vw          Uo          Ho          Hi          Qp         Txf
  #   (degC)   (m/s)    (W/m^2-K)   (W/m^2-K)   (W/m^2-K)    (W/m^2)     (degC)

  1    30.53    4.19    5.512E+03   9.429E+03   3.348E+04   1.683E+05    17.85
  2    30.31    3.67    5.451E+03   9.587E+03   2.995E+04   1.652E+05    17.23
  3    30.43    3.16    5.318E+03   9.612E+03   2.639E+04   1.618E+05    16.84
  4    30.60    2.65    5.206E+03   9.858E+03   2.270E+04   1.593E+05    16.16
  5    30.57    2.14    5.028E+03   1.011E+04   1.896E+04   1.537E+05    15.20
  6    30.49    1.63    4.724E+03   1.028E+04   1.511E+04   1.440E+05    14.01
  7    30.54    1.12    4.288E+03   1.075E+04   1.108E+04   1.310E+05    12.19
  8    30.58    1.12    4.296E+03   1.081E+04   1.107E+04   1.313E+05    12.16
  9    30.67    1.63    4.787E+03   1.060E+04   1.508E+04   1.468E+05    13.86
 10    31.11    2.14    4.971E+03   9.915E+03   1.885E+04   1.547E+05    15.60
 11    31.19    2.65    5.222E+03   9.948E+03   2.255E+04   1.629E+05    16.37
 12    31.32    3.16    5.390E+03   9.881E+03   2.612E+04   1.688E+05    17.06
 13    31.07    3.67    5.532E+03   9.874E+03   2.969E+04   1.719E+05    17.41
 14    31.10    4.19    5.594E+03   9.704E+03   3.314E+04   1.740E+05    17.93
Avg                                 1.003E+04               1.567E+05    15.70
```

```
Program Name:                 DRPALL
Raw data stored on file:      SSMTA2
Data taken by:                INCHECK
Tube type:                    SMOOTH TUBE
Tube material:                STAINLESS-STEEL
Thermal conductivity:          14.3 (W/m-K)
Inside diameter:               13.21 (mm)
Root diameter:                 14.10 (mm)
Pressure condition:           ATMOSPHERIC

            Room     Inlet   Outlet    Steam     Gage    Xducer
      Flow  Temp     Temp     Temp     Temp     Press    Press    Volts   Current
     (pct) (degC)   (degC)   (degC)   (degC)    (KPa)    (KPa)     (V)

  1   80   20.01    17.92    19.29    100.1    100.7    100.3    384.7    2.74
  2   70   20.01    18.39    19.92    100.0    101.0    100.6    385.1    2.74
  3   60   20.02    18.51    20.36    100.1    100.9    100.6    385.0    2.74
  4   50   20.00    18.61    20.61    100.0    100.7    100.5    385.2    2.74
  5   40   20.00    18.76    21.15    100.0    100.5    100.4    384.7    2.73
  6   30   20.07    18.92    21.90    100.1    100.0    100.5    385.1    2.73
  7   20   20.08    19.05    23.07    100.1     99.9    100.4    384.7    2.73
  8   20   20.04    19.05    23.08    100.1    100.0    100.5    385.1    2.73
  9   30   20.06    19.05    22.04    100.1    100.0    100.7    384.9    2.73
 10   40   20.08    18.99    21.39    100.0     99.6    100.4    385.0    2.72
 11   50   20.10    19.18    21.18    100.1     99.8    100.5    385.1    2.73
 12   60   20.13    19.20    20.93    100.2    100.3    100.9    385.1    2.73
 13   70   20.15    19.40    20.92    100.1    100.0    100.6    384.9    2.73
 14   80   20.16    19.47    20.83    100.1    100.0    100.7    385.1    2.73
```

```
Program Name:                     DRPALL
Raw data stored on file:          SSMTA2
Data taken by:                    INCHECK
Tube type:                        SMOOTH TUBE
Tube material:                    STAINLESS-STEEL
Thermal conductivity:              14.3 (W/m-K)
Inside diameter:                   13.21 (mm)
Root diameter:                     14.10 (mm)
Pressure condition:               ATMOSPHERIC
System power:                      25.73 (KW)
Steam velocity:                     1.03 (m/s)
This analysis includes end-fin effect
HEATEX insert installed in tube

Wilson Plot regression coefficient = 0.998
Ci (based on Petukhov-Popov)       = 3.011
Alpha (based on Nusselt)           = 0.627

                         Overall     Outside     Inside
               Coolant  Heat Xfer   Heat Xfer   Heat Xfer      Heat
              Velocity Coefficient Coefficient Coefficient     Flux       Ts-Twall
Data   LMTD      Vw         Uo          Ho          Hi          Qp          Txf
  #   (degC)   (m/s)   (W/m^2-K)   (W/m^2-K)   (W/m^2-K)    (W/m^2)      (degC)

  1    81.47    4.11   6.416E+03   9.882E+03   4.712E+04   5.227E+05    52.90
  2    80.84    3.61   6.372E+03   1.002E+04   4.247E+04   5.151E+05    51.41
  3    80.58    3.11   6.355E+03   1.031E+04   3.756E+04   5.121E+05    49.66
  4    80.35    2.61   6.135E+03   1.019E+04   3.243E+04   4.930E+05    48.38
  5    80.05    2.11   5.948E+03   1.031E+04   2.720E+04   4.761E+05    46.20
  6    79.71    1.61   5.714E+03   1.061E+04   2.178E+04   4.555E+05    42.93
  7    79.05    1.10   5.346E+03   1.122E+04   1.606E+04   4.226E+05    37.65
  8    78.99    1.10   5.357E+03   1.127E+04   1.607E+04   4.231E+05    37.54
  9    79.52    1.61   5.740E+03   1.069E+04   2.181E+04   4.564E+05    42.69
 10    79.80    2.11   6.000E+03   1.045E+04   2.727E+04   4.788E+05    45.81
 11    79.89    2.61   6.165E+03   1.025E+04   3.263E+04   4.926E+05    48.05
 12    80.12    3.11   6.325E+03   1.022E+04   3.780E+04   5.068E+05    49.61
 13    79.96    3.61   6.443E+03   1.017E+04   4.295E+04   5.152E+05    50.67
 14    79.96    4.12   6.486E+03   1.001E+04   4.795E+04   5.186E+05    51.81
Avg                                1.040E+04               4.849E+05    46.81
```

```
          Program Name:                 DRPALL
          Raw data stored on file:      SSMTA3
          Data taken by:                INCHECK
          Tube type:                    SMOOTH TUBE
          Tube material:                STAINLESS-STEEL
          Thermal conductivity:          14.3 (W/m-K)
          Inside diameter:               13.21 (mm)
          Root diameter:                 14.10 (mm)
          Pressure condition:           ATMOSPHERIC

             Room    Inlet   Outlet   Steam    Gage    Xducer
      Flow  Temp     Temp     Temp    Temp    Press    Press    Volts   Current
     (pct) (degC)  (degC)  (degC)  (degC)   (KPa)    (KPa)     (V)

  1   80   20.20    19.85    21.20   100.0    99.9    100.5    385.1    2.73
  2   70   20.22    19.92    21.42   100.1   100.0    100.6    385.2    2.73
  3   60   20.22    20.02    21.74   100.0    99.8    100.5    384.9    2.73
  4   50   20.25    19.85    21.84   100.0    99.6    100.4    384.9    2.74
  5   40   20.27    19.83    22.22   100.1    99.9    100.6    385.0    2.74
  6   30   20.30    20.04    23.01   100.1   100.0    100.7    385.1    2.74
  7   20   20.28    19.92    23.89    99.8    99.3    100.2    384.6    2.72
  8   20   20.29    19.88    23.87   100.0   100.1    100.8    385.0    2.73
  9   30   20.31    19.81    22.79   100.0   100.0    100.5    385.2    2.73
 10   40   20.34    19.69    22.07   100.1   100.0    100.7    385.1    2.73
 11   50   20.31    19.75    21.74   100.2   100.0    100.7    384.6    2.73
 12   60   20.35    19.79    21.51    99.8    99.3     99.8    385.2    2.73
 13   70   20.32    19.97    21.49   100.1   100.1    100.8    384.5    2.73
 14   80   20.36    20.02    21.38    99.9    99.6    100.4    384.9    2.74
```

```
            Program Name:                     DRPALL
            Raw data stored on file:          SSMTA3
            Data taken by:                    INCHECK
            Tube type:                        SMOOTH TUBE
            Tube material:                    STAINLESS-STEEL
            Thermal conductivity:              14.3 (W/m-K)
            Inside diameter:                   13.21 (mm)
            Root diameter:                     14.10 (mm)
            Pressure condition:               ATMOSPHERIC
            System power:                      25.73 (KW)
            Steam velocity:                     4.03 (m/s)
            This analysis includes end-fin effect
            HEATEX insert installed in tube

            Wilson Plot regression coefficient = 0.999
            Ci (based on Petukhov-Popov)       = 3.007
            Alpha (based on Nusselt)           = 0.827

                                Overall     Outside      Inside
                     Coolant   Heat Xfer   Heat Xfer    Heat Xfer      Heat
                    Velocity Coefficient Coefficient  Coefficient      Flux     Ts-Twall
       Data   LMTD     Vw         Uo          Ho           Hi           Qp         Txf
        #   (degC)   (m/s)   (W/m^2-K)   (W/m^2-K)    (W/m^2-K)     (W/m^2)    (degC)

        1    79.53    4.12   6.459E+03   9.941E+03    4.809E+04    5.137E+05    51.68
        2    79.40    3.61   6.401E+03   1.005E+04    4.314E+04    5.082E+05    50.56
        3    79.12    3.11   6.362E+03   1.029E+04    3.810E+04    5.033E+05    48.93
        4    79.17    2.61   6.207E+03   1.034E+04    3.284E+04    4.914E+05    47.51
        5    79.03    2.11   6.023E+03   1.049E+04    2.750E+04    4.760E+05    45.39
        6    78.56    1.61   5.782E+03   1.078E+04    2.202E+04    4.542E+05    42.13
        7    77.88    1.10   5.352E+03   1.118E+04    1.620E+04    4.168E+05    37.27
        8    78.12    1.10   5.367E+03   1.125E+04    1.619E+04    4.193E+05    37.26
        9    78.70    1.61   5.777E+03   1.078E+04    2.197E+04    4.547E+05    42.17
       10    79.26    2.11   6.001E+03   1.043E+04    2.745E+04    4.756E+05    45.62
       11    79.42    2.61   6.175E+03   1.026E+04    3.280E+04    4.904E+05    47.80
       12    79.14    3.11   6.345E+03   1.025E+04    3.801E+04    5.022E+05    48.99
       13    79.34    3.61   6.463E+03   1.020E+04    4.317E+04    5.128E+05    50.25
       14    79.23    4.12   6.506E+03   1.005E+04    4.818E+04    5.155E+05    51.30
       Avg                               1.045E+04                 4.810E+05    46.20
```

```
           Program Name:                 DRPALL
           Raw data stored on file:      S16A1
           Data taken by:                INCHECK
           Tube type:                    RECTANGULAR FINNED TUBE
           Fin spacing, width, height:   1.50  1.00  0.16 (mm)
           Tube material:                STAINLESS-STEEL
           Thermal conductivity:          14.3 (W/m-K)
           Inside diameter:               13.20 (mm)
           Root diameter:                 14.25 (mm)
           Pressure condition:           ATMOSPHERIC

            Room    Inlet   Outlet   Steam    Gage   Xducer
      Flow  Temp    Temp    Temp     Temp     Press  Press  Volts  Current
     (pct) (degC)  (degC)  (degC)   (degC)    (KPa)  (KPa)   (V)

 1    80   19.80   17.78   19.43    100.0    100.3  100.2   384.9   2.73
 2    70   19.87   18.30   20.13    100.0    100.7  100.6   385.1   2.74
 3    60   19.87   18.51   20.57    100.0    100.7  100.4   385.0   2.74
 4    50   19.87   18.51   20.89     99.9    100.2  100.3   385.0   2.74
 5    40   19.91   18.58   21.38    100.2    100.9  101.1   385.1   2.73
 6    30   19.90   18.66   22.16     99.9     99.3   99.9   385.1   2.74
 7    20   19.90   18.84   23.48    100.0     99.6  100.4   385.0   2.74
 8    20   19.90   18.88   23.52    100.1     99.6  100.4   385.2   2.74
 9    30   19.91   18.87   22.37     99.8     99.3   99.8   385.0   2.74
10    40   19.90   18.78   21.62    100.1     99.6  100.6   385.0   2.74
11    50   19.91   18.96   21.34    100.0     99.3  100.2   385.3   2.75
12    60   19.90   19.02   21.09    100.1    100.0  100.5   385.0   2.74
13    70   19.92   19.22   21.05    100.0     99.6  100.3   384.9   2.74
14    80   19.90   19.30   20.92     99.9     99.1  100.1   385.0   2.74
```

```
Program Name:                   DRFALL
Raw data stored on file:        S16A1
Data taken by:                  INCHECK
Tube type:                      RECTANGULAR FINNED TUBE
Fin spacing, width, height:     1.50  1.00  0.16 (mm)
Tube material:                  STAINLESS-STEEL
Thermal conductivity:           14.3 (W/m-K)
Inside diameter:                 13.20 (mm)
Root diameter:                   14.25 (mm)
Pressure condition:             ATMOSPHERIC
System power:                    25.74 (KW)
Steam velocity:                   1.03 (m/s)
This analysis includes end-fin affect
HEATEX insert installed in tube
Enhancements based on comparison to Incheck smooth tube data

Wilson Plot regression coefficient = 0.998
Ci (based on Petukhov-Popov)        = 3.171
Alpha (based on Nusselt)            = 1.106
Enhancement (constant heat flux)    = 1.473
Enhancement (constant temp drop)    = 1.337

                        Overall     Outside     Inside
              Coolant  Heat Xfer   Heat Xfer   Heat Xfer     Heat
             Velocity Coefficient Coefficient Coefficient    Flux      Ts-Twall
Data   LMTD     Vw        Uo          Ho          Hi          Qp         Txf
 #   (degC)   (m/s)   (W/m^2-K)   (W/m^2-K)   (W/m^2-K)    (W/m^2)    (degC)

  1   81.43   4.12    7.638E+03   1.405E+04   4.970E+04   6.220E+05   44.28
  2   80.83   3.62    7.570E+03   1.428E+04   4.482E+04   6.119E+05   42.84
  3   80.47   3.12    7.408E+03   1.433E+04   3.954E+04   5.961E+05   41.61
  4   80.23   2.61    7.262E+03   1.465E+04   3.423E+04   5.826E+05   39.77
  5   80.20   2.11    6.917E+03   1.447E+04   2.870E+04   5.547E+05   38.34
  6   79.44   1.61    6.655E+03   1.526E+04   2.297E+04   5.287E+05   34.64
  7   78.83   1.11    6.115E+03   1.603E+04   1.696E+04   4.821E+05   30.08
  8   78.83   1.11    6.125E+03   1.609E+04   1.697E+04   4.829E+05   30.01
  9   79.19   1.61    6.680E+03   1.536E+04   2.302E+04   5.289E+05   34.43
 10   79.91   2.11    7.036E+03   1.488E+04   2.877E+04   5.623E+05   37.54
 11   79.82   2.61    7.291E+03   1.473E+04   3.441E+04   5.819E+05   39.50
 12   80.06   3.12    7.489E+03   1.460E+04   3.987E+04   5.995E+05   41.07
 13   79.86   3.62    7.664E+03   1.457E+04   4.528E+04   6.121E+05   42.02
 14   79.81   4.12    7.714E+03   1.423E+04   5.055E+04   6.157E+05   43.26
Avg                               1.483E+04               5.687E+05   38.53
```

```
Program Name:                  DRPALL
Raw data stored on file:       S16A2
Data taken by:                 INCHECK
Tube type:                     RECTANGULAR FINNED TUBE
Fin spacing, width, height:    1.50  1.00  0.16 (mm)
Tube material:                 STAINLESS-STEEL
Thermal conductivity:           14.3 (W/m-K)
Inside diameter:                13.20 (mm)
Root diameter:                  14.26 (mm)
Pressure condition:            ATMOSPHERIC

            Room     Inlet   Outlet    Steam     Gage    Xducer
     Flow   Temp     Temp     Temp     Temp     Press    Press.    Volts   Current
    (pct) (degC)   (degC)   (degC)   (degC)    (KPa)    (KPa)     (V)

 1   80    19.88    19.49    21.11    100.0     99.6    100.4    385.2     2.74
 2   70    19.98    19.63    21.43    100.1     99.6    100.5    385.3     2.73
 3   60    19.98    19.72    21.76     99.9     99.2    100.0    385.0     2.73
 4   50    19.96    19.62    21.99    100.0     99.3    100.2    384.8     2.73
 5   40    19.95    19.52    22.33     99.9     99.1    100.1    384.9     2.74
 6   30    19.98    19.55    23.04    100.1     99.7    100.5    384.8     2.74
 7   20    19.97    19.58    24.28    100.1    100.0    100.7    385.1     2.74
 8   20    19.98    19.64    24.25    100.0     99.3    100.3    385.0     2.74
 9   30    19.95    19.50    22.98    100.0     99.1     99.9    384.8     2.74
10   40    19.98    19.39    22.20    100.0     99.3    100.0    385.0     2.74
11   50    20.01    19.49    21.88    100.2    100.0    100.8    385.0     2.73
12   60    20.04    19.52    21.59    100.1     99.8    100.6    385.0     2.73
13   70    20.04    19.74    21.56    100.2    100.0    100.9    385.1     2.74
14   80    20.01    19.76    21.40     99.8     98.6     99.6    384.7     2.73
```

```
Program Name:                   DRPALL
Raw data stored on file:        S16A2
Data taken by:                  INCHECK
Tube type:                      RECTANGULAR FINNED TUBE
Fin spacing, width, height:     1.50  1.00  0.15 (mm)
Tube material:                  STAINLESS-STEEL
Thermal conductivity:            14.3 (W/m-K)
Inside diameter:                 13.20 (mm)
Root diameter:                   14.28 (mm)
Pressure condition:             ATMOSPHERIC
System power:                    25.73 (KW)
Steam velocity:                   1.03 (m/s)
This analysis includes end-fin effect
HEATEX insert installed in tube
Enhancements based on comparison to Incheck smooth tube data

Wilson Plot regression coefficient = 0.998
Ci (based on Petukhov-Popov)       = 3.102
Alpha (based on Nusselt)           = 1.117
Enhancement (constant heat flux)   = 1.494
Enhancement (constant temp drop)   = 1.351

                        Overall     Outside     Inside
              Coolant  Heat Xfer   Heat Xfer   Heat Xfer     Heat
              Velocity Coefficient Coefficient Coefficient   Flux      Ts-Twall
Data   LMTD     Vw        Uo          Ho          Hi          Qp         Txf
 #   (degC)   (m/s)   (W/m^2-K)   (W/m^2-K)   (W/m^2-K)    (W/m^2)    (degC)

 1    79.76   4.12    7.673E+03   1.418E+04   4.856E+04   6.120E+05   43.17
 2    79.58   3.62    7.590E+03   1.438E+04   4.450E+04   6.040E+05   41.98
 3    79.15   3.12    7.467E+03   1.460E+04   3.931E+04   5.910E+05   40.49
 4    79.15   2.61    7.303E+03   1.488E+04   3.391E+04   5.780E+05   38.84
 5    79.00   2.11    7.034E+03   1.509E+04   2.838E+04   5.557E+05   36.83
 6    78.75   1.61    6.696E+03   1.561E+04   2.270E+04   5.273E+05   33.78
 7    78.09   1.11    6.129E+03   1.634E+04   1.675E+04   4.786E+05   29.30
 8    78.05   1.11    6.134E+03   1.638E+04   1.674E+04   4.787E+05   29.23
 9    78.76   1.61    6.665E+03   1.545E+04   2.268E+04   5.249E+05   33.97
10    79.25   2.11    7.021E+03   1.504E+04   2.833E+04   5.564E+05   37.00
11    79.50   2.61    7.354E+03   1.511E+04   3.387E+04   5.846E+05   38.70
12    79.58   3.12    7.573E+03   1.502E+04   3.922E+04   6.026E+05   40.12
13    79.53   3.62    7.647E+03   1.459E+04   4.456E+04   6.082E+05   41.70
14    79.25   4.12    7.849E+03   1.477E+04   4.971E+04   6.220E+05   42.10
Avg                               1.510E+04               5.660E+05   37.66
```

```
          Program Name:                  DRPALL
          Raw data stored on file:       S28A1
          Data taken by:                 INCHECK
          Tube type:                     RECTANGULAR FINNED TUBE
          Fin spacing, width, height:    1.50  1.00  0.28 (mm)
          Tube material:                 STAINLESS-STEEL
          Thermal conductivity:           14.3 (W/m-K)
          Inside diameter:                13.15 (mm)
          Root diameter:                  14.23 (mm)
          Pressure condition:            ATMOSPHERIC

               Room     Inlet    Outlet    Steam     Gage    Xducer
       Flow    Temp     Temp     Temp      Temp      Press   Press -   Volts   Current
       (pct) (degC)   (degC)   (degC)    (degC)    (KPa)   (KPa)      (V)

  1     80    20.12    18.24    20.05     100.5     102.0   101.6    385.0     2.74
  2     70    20.15    18.70    20.70     100.1     101.4   100.7    384.9     2.74
  3     60    20.18    19.02    21.27     100.3     101.4   100.7    385.0     2.75
  4     50    20.18    19.07    21.66     100.1     101.4   100.6    384.9     2.74
  5     40    20.21    19.21    22.27     100.1     101.0   100.4    385.0     2.74
  6     30    20.21    19.35    23.12     100.1     100.7   100.6    384.9     2.74
  7     20    20.25    19.53    24.45     100.2     100.0   100.7    385.1     2.74
  8     20    20.26    19.53    24.46     100.0     100.0   100.4    385.0     2.74
  9     30    20.27    19.52    23.27      99.9      99.3    99.9    384.9     2.74
 10     40    20.29    19.54    22.62     100.1     100.0   100.6    384.9     2.74
 11     50    20.32    19.66    22.25      99.9      99.6   100.0    385.1     2.75
 12     60    20.31    19.81    22.07     100.1     100.0   100.5    384.9     2.75
 13     70    20.35    20.16    22.16     100.1     100.0   100.3    384.9     2.74
 14     80    20.36    20.28    22.07     100.1     100.0   100.5    385.0     2.74
```

```
        Program Name:                 DRPALL
        Raw data stored on file:      S28A1
        Data taken by:                INCHECK
        Tube type:                    RECTANGULAR FINNED TUBE
        Fin spacing, width, height:   1.50  1.00  0.28 (mm)
        Tube material:                STAINLESS-STEEL
        Thermal conductivity:          14.3 (W/m-K)
        Inside diameter:               13.15 (mm)
        Root diameter:                 14.23 (mm)
        Pressure condition:           ATMOSPHERIC
        System power:                  25.73 (KW)
        Steam velocity:                 1.03 (m/s)
        This analysis includes end-fin effect
        HEATEX insert installed in tube
        Enhancements based on comparison to Incheck smooth tube data

        Wilson Plot regression coefficient = 0.999
        Ci (based on Petukhov-Popov)       = 3.081
        Alpha (based on Nusselt)           = 1.328
        Enhancement (constant heat flux)   = 1.881
        Enhancement (constant temp drop)   = 1.606

                           Overall     Outside     Inside
                  Coolant  Heat Xfer   Heat Xfer   Heat Xfer      Heat
                 Velocity Coefficient Coefficient Coefficient     Flux       Ts-Twall
Data    LMTD       Vw`       Uo          Ho          Hi            Qp          Txf
  #    (degC)    (m/s)   (W/m^2-K)   (W/m^2-K)   (W/m^2-K)     (W/m^2)      (degC)

  1    81.35     4.15    8.441E+03   1.748E+04   4.894E+04    6.867E+05     39.28
  2    80.45     3.65    8.351E+03   1.783E+04   4.411E+04    6.719E+05     37.68
  3    80.13     3.14    8.177E+03   1.802E+04   3.906E+04    6.553E+05     36.37
  4    79.78     2.63    7.948E+03   1.827E+04   3.376E+04    6.341E+05     34.70
  5    79.38     2.13    7.632E+03   1.857E+04   2.833E+04    6.058E+05     32.63
  6    78.88     1.62    7.230E+03   1.932E+04   2.269E+04    5.703E+05     29.52
  7    78.18     1.11    6.548E+03   2.019E+04   1.675E+04    5.119E+05     25.35
  8    78.01     1.11    6.573E+03   2.043E+04   1.676E+04    5.128E+05     25.10
  9    78.47     1.62    7.230E+03   1.928E+04   2.273E+04    5.673E+05     29.42
 10    79.01     2.13    7.723E+03   1.906E+04   2.843E+04    6.102E+05     32.01
 11    78.94     2.63    8.011E+03   1.854E+04   3.398E+04    6.324E+05     34.12
 12    79.17     3.14    8.321E+03   1.864E+04   3.941E+04    6.588E+05     35.33
 13    78.92     3.65    8.482E+03   1.830E+04   4.482E+04    6.694E+05     36.58
 14    78.95     4.15    8.585E+03   1.795E+04   5.006E+04    6.778E+05     37.77
Avg                                  1.871E+04                6.189E+05     33.28
```

```
         Program Name:                    DRPALL
         Raw data stored on file:         S28A2
         Data taken by:                   INCHECK
         Tube type:                       RECTANGULAR FINNED TUBE
         Fin spacing, width, height:      1.50  1.00  0.28 (mm)
         Tube material:                   STAINLESS-STEEL
         Thermal conductivity:             14.3 (W/m-K)
         Inside diameter:                  13.15 (mm)
         Root diameter:                    14.23 (mm)
         Pressure condition:              ATMOSPHERIC

           Room    Inlet   Outlet   Steam    Gage    Xducer
     Flow  Temp    Temp    Temp     Temp     Press   Press    Volts   Current
    (pct) (degC)  (degC)  (degC)   (degC)   (KPa)   (KPa)     (V)

  1   80   19.98   18.33   20.09   100.0    100.7   100.5    384.9    2.75
  2   70   19.96   18.66   20.60   100.0    100.7   100.3    385.0    2.75
  3   60   19.98   19.01   21.20   100.0    100.1   100.2    384.9    2.75
  4   50   19.99   19.02   21.53   100.1    100.7   100.6    384.8    2.75
  5   40   19.99   19.16   22.11    99.9     99.8   100.2    384.8    2.75
  6   30   20.04   19.39   23.03   100.1     99.9   100.5    385.2    2.75
  7   20   20.11   19.58   24.36    99.8     99.1    99.6    385.1    2.75
  8   20   20.11   19.61   24.40   100.2    100.5   100.9    384.9    2.75
  9   30   20.02   19.78   23.41   100.0    100.0   100.5    384.9    2.74
 10   40   20.01   19.72   22.70   100.0    100.3   100.8    385.0    2.75
 11   50   20.07   19.87   22.39   100.0    100.0   100.6    385.0    2.75
 12   60   20.04   19.90   22.11    99.9     99.3   100.1    385.0    2.75
 13   70   20.07   20.18   22.12   100.0    100.0   100.5    384.9    2.75
 14   80   20.05   20.31   22.05   100.0     99.9   100.3    384.9    2.75
```

```
Program Name:                  DRPALL
Raw data stored on file;       S28A2
Data taken by:                 INCHECK
Tube type:                     RECTANGULAR FINNED TUBE
Fin spacing, width, height:    1.50  1.00  0.29 (mm)
Tube material:                 STAINLESS-STEEL
Thermal conductivity:           14.3 (W/m-K)
Inside diameter:                13.15 (mm)
Root diameter:                  14.22 (mm)
Pressure condition:            ATMOSPHERIC
System power:                   25.73 (KW)
Steam velocity:                  1.03 (m/s)
This analysis includes end-fin affect
HEATEX insert installed in tube
Enhancements based on comparison to Incheck smooth tube data

Wilson Plot regression coefficient = 0.988
Ci (based on Petukhov-Popov)       = 2.853
Alpha (based on Nusselt)           = 1.281
Enhancement (constant heat flux)   = 1.782
Enhancement (constant temp drop)   = 1.549

                        Overall      Outside      Inside
              Coolant   Heat Xfer    Heat Xfer    Heat Xfer      Heat
              Velocity Coefficient Coefficient  Coefficient      Flux       Ts-Twall
Data   LMTD     Vw         Uo           Ho           Hi           Qp          Txf
 #   (degC)   (m/s)   (W/m^2-K)    (W/m^2-K)    (W/m^2-K)     (W/m^2)      (degC)

  1   80.84    4.15    8.207E+03    1.675E+04    4.694E+04    6.634E+05    39.59
  2   80.39    3.65    8.112E+03    1.708E+04    4.224E+04    6.521E+05    38.18
  3   79.91    3.14    7.963E+03    1.736E+04    3.742E+04    6.363E+05    36.65
  4   79.84    2.63    7.695E+03    1.741E+04    3.232E+04    6.143E+05    35.29
  5   79.29    2.13    7.371E+03    1.760E+04    2.712E+04    5.845E+05    33.21
  6   78.84    1.62    6.977E+03    1.827E+04    2.174E+04    5.500E+05    30.10
  7   77.85    1.11    6.390E+03    1.979E+04    1.605E+04    4.974E+05    25.14
  8   78.16    1.11    6.375E+03    1.964E+04    1.606E+04    4.982E+05    25.37
  9   78.35    1.62    7.018E+03    1.849E+04    2.183E+04    5.499E+05    29.74
 10   78.84    2.13    7.492E+03    1.822E+04    2.729E+04    5.906E+05    32.41
 11   78.86    2.63    7.831E+03    1.801E+04    3.263E+04    6.176E+05    34.28
 12   78.95    3.14    8.134E+03    1.811E+04    3.780E+04    6.422E+05    35.47
 13   78.90    3.65    8.245E+03    1.755E+04    4.296E+04    6.505E+05    37.07
 14   78.87    4.15    8.395E+03    1.743E+04    4.798E+04    6.624E+05    38.01
Avg                                 1.798E+04                 6.007E+05    33.61
```

```
Program Name:                    DRPALL
Raw data stored on file:         S28A3
Data taken by:                   INCHECK
Tube type:                       RECTANGULAR FINNED TUBE
Fin spacing, width, height:      1.50  1.00  0.28 (mm)
Tube material:                   STAINLESS-STEEL
Thermal conductivity:             14.3 (W/m-K)
Inside diameter:                  13.15 (mm)
Root diameter:                    14.23 (mm)
Pressure condition:              ATMOSPHERIC

              Room     Inlet    Outlet    Steam     Gage    Xducer
      Flow    Temp     Temp     Temp      Temp      Press   Press     Volts   Current
     (pct) (degC)   (degC)   (degC)    (degC)    (KPa)   (KPa)     (V)

 1    80    19.42    18.21    19.95     100.1     101.4   100.8     384.9    2.75
 2    70    19.45    18.55    20.47     100.1     100.9   100.6     384.8    2.73
 3    60    19.47    18.69    20.87     100.1     100.9   100.6     385.0    2.74
 4    50    19.53    18.70    21.22     100.1     100.1   100.5     385.0    2.74
 5    40    19.53    18.87    21.84     100.1     100.0   100.4     385.0    2.73
 6    30    19.56    19.01    22.66     100.0     100.0   100.4     385.2    2.73
 7    20    19.59    19.23    24.01     100.1     100.1   100.4     385.0    2.73
 8    20    19.61    19.22    24.02     100.1      99.6   100.2     385.3    2.72
 9    30    19.64    19.24    22.88     100.0     100.0   100.4     384.9    2.73
10    40    19.62    19.27    22.24     100.1     100.1   100.5     384.7    2.72
11    50    19.64    19.27    21.79     100.2     100.5   100.8     385.3    2.72
12    60    19.66    19.33    21.52     100.1     100.3   100.7     384.8    2.72
13    70    19.65    19.54    21.57     100.0      99.9   100.4     385.1    2.71
14    80    19.54    19.70    21.45     100.1     100.3   100.8     384.8    2.71
```

```
Program Name:                   DRPALL
Raw data stored on file:        S28A3
Data taken by:                  INCHECK
Tube type:                      RECTANGULAR FINNED TUBE
Fin spacing, width, height:     1.50  1.00  0.25 (mm)
Tube material:                  STAINLESS-STEEL
Thermal conductivity:            14.3 (W/m-K)
Inside diameter:                 13.15 (mm)
Root diameter:                   14.23 (mm)
Pressure condition:             ATMOSPHERIC
System power:                    25.73 (KW)
Steam velocity:                   1.03 (m/s)
This analysis includes end-fin effect
HEATEX insert installed in tube
Enhancements based on comparison to Incheck smooth tube data

Wilson Plot regression coefficient = 0.899
Ci (based on Petukhov-Popov)        = 3.014
Alpha (based on Nusselt)            = 1.257
Enhancement (constant heat flux)    = 1.747
Enhancement (constant temp drop)    = 1.519

                      Overall     Outside      Inside
           Coolant   Heat Xfer   Heat Xfer   Heat Xfer      Heat
          Velocity Coefficient Coefficient Coefficient      Flux      Ts-Twall
Data  LMTD    Vw        Uo          Ho          Hi           Qp          Txf
 #  (degC)  (m/s)   (W/m^2-K)   (W/m^2-K)   (W/m^2-K)    (W/m^2)      (degC)

 1   81.05   4.15   8.126E+03   1.631E+04   4.784E+04   6.586E+05    40.38
 2   80.62   3.65   8.007E+03   1.649E+04   4.306E+04   6.455E+05    39.15
 3   80.35   3.14   7.866E+03   1.678E+04   3.806E+04   6.321E+05    37.68
 4   80.13   2.63   7.710E+03   1.731E+04   3.287E+04   6.178E+05    35.63
 5   79.74   2.13   7.368E+03   1.738E+04   2.759E+04   5.875E+05    33.81
 6   79.17   1.62   6.974E+03   1.789E+04   2.209E+04   5.521E+05    30.69
 7   78.45   1.11   6.344E+03   1.896E+04   1.632E+04   4.977E+05    26.25
 8   78.44   1.11   6.359E+03   1.909E+04   1.632E+04   4.987E+05    26.13
 9   78.93   1.62   6.986E+03   1.803E+04   2.215E+04   5.514E+05    30.58
10   79.31   2.13   7.439E+03   1.772E+04   2.772E+04   5.899E+05    33.30
11   79.71   2.63   7.739E+03   1.740E+04   3.308E+04   6.169E+05    35.46
12   79.68   3.14   8.004E+03   1.735E+04   3.833E+04   6.377E+05    36.75
13   79.41   3.65   8.167E+03   1.709E+04   4.359E+04   6.486E+05    37.94
14   79.53   4.15   8.329E+03   1.704E+04   4.865E+04   6.624E+05    38.88
Avg                             1.750E+04               5.998E+05    34.48
```

```
Program Name:                     DRPALL
Raw data stored on file:          S38A1
Data taken by:                    INCHECK
Tube type:                        RECTANGULAR FINNED TUBE
Fin spacing, width, height:       1.50  1.00  0.38 (mm)
Tube material:                    STAINLESS-STEEL
Thermal conductivity:              14.3 (W/m-K)
Inside diameter:                   13.08 (mm)
Root diameter:                     14.29 (mm)
Pressure condition:               ATMOSPHERIC

            Room     Inlet   Outlet    Steam     Gage    Xducer
      Flow  Temp     Temp     Temp     Temp     Press    Press   Volts   Current
     (pct) (degC)   (degC)   (degC)   (degC)    (KPa)    (KPa)    (V)

  1    80   20.97    18.08    19.62     99.5     98.6     98.7   384.8    2.74
  2    70   20.98    18.48    20.20    100.1    101.4    101.0   385.0    2.74
  3    60   21.01    18.77    20.71    100.1    100.7    100.6   384.5    2.74
  4    50   21.03    18.75    21.00    100.0    100.7    100.5   385.1    2.74
  5    40   21.06    18.96    21.62    100.0     99.6    100.5   385.1    2.74
  6    30   21.08    19.16    22.46     99.9     99.3    100.2   384.9    2.74
  7    20   21.12    19.32    23.67    100.0     99.3    100.2   385.2    2.74
  8    20   21.11    19.32    23.68     99.9     99.3    100.2   384.9    2.74
  9    30   21.12    19.31    22.60     99.9    100.0     99.9   384.9    2.74
 10    40   21.14    19.20    21.85    100.0     99.3    100.1   385.1    2.74
 11    50   21.14    19.24    21.50    100.0     99.5    100.5   384.9    2.74
 12    60   21.15    19.34    21.30     99.9     99.5    100.5   385.0    2.74
 13    70   21.16    19.53    21.25    100.0     99.1    100.1   385.1    2.74
 14    80   21.17    19.54    21.09    100.0     99.6    100.7   385.0    2.74
```

```
Program Name:                  DRPALL
Raw data stored on file:       S3SA1
Data taken by:                 INCHECK
Tube type:                     RECTANGULAR FINNED TUBE
Fin spacing, width, height:    1.50  1.00  0.38 (mm)
Tube material:                 STAINLESS-STEEL
Thermal conductivity:           14.3 (W/m-K)
Inside diameter:                13.08 (mm)
Root diameter:                  14.29 (mm)
Pressure condition:            ATMOSPHERIC
System power:                   25.73 (KW)
Steam velocity:                  1.03 (m/s)
This analysis includes end-fin effect
HEATEX insert installed in tube
Enhancements based on comparison to Incheck smooth tube data

Wilson Plot regression coefficient  = 0.999
Ci (based on Petukhov-Popov)        = 2.945
Alpha (based on Nusselt)            = 1.085
Enhancement (constant heat flux)    = 1.437
Enhancement (constant temp drop)    = 1.313

                        Overall    Outside    Inside
              Coolant  Heat Xfer  Heat Xfer  Heat Xfer     Heat
             Velocity Coefficient Coefficient Coefficient  Flux     Ts-Twall
Data   LMTD     Vw         Uo         Ho         Hi         Qp        Txf
  #   (degC)  (m/s)   (W/m^2-K)  (W/m^2-K)  (W/m^2-K)   (W/m^2)   (degC)

  1   80.66   4.20   7.198E+03  1.395E+04  4.709E+04  5.806E+05   41.62
  2   80.75   3.69   7.119E+03  1.415E+04  4.241E+04  5.748E+05   40.63
  3   80.33   3.17   7.006E+03  1.436E+04  3.753E+04  5.628E+05   39.19
  4   80.11   2.66   6.855E+03  1.466E+04  3.241E+04  5.491E+05   37.47
  5   79.71   2.15   6.590E+03  1.476E+04  2.721E+04  5.253E+05   35.58
  6   79.10   1.64   6.287E+03  1.534E+04  2.180E+04  4.973E+05   32.43
  7   78.48   1.13   5.753E+03  1.601E+04  1.608E+04  4.515E+05   28.20
  8   78.41   1.13   5.761E+03  1.608E+04  1.608E+04  4.518E+05   28.10
  9   78.98   1.64   6.276E+03  1.525E+04  2.183E+04  4.956E+05   32.50
 10   79.45   2.15   6.621E+03  1.490E+04  2.728E+04  5.260E+05   35.31
 11   79.67   2.66   6.921E+03  1.492E+04  3.258E+04  5.513E+05   36.95
 12   79.62   3.17   7.104E+03  1.474E+04  3.778E+04  5.656E+05   38.38
 13   79.59   3.69   7.208E+03  1.444E+04  4.291E+04  5.737E+05   39.73
 14   79.75   4.20   7.319E+03  1.434E+04  4.787E+04  5.836E+05   40.71
Avg                              1.485E+04             5.349E+05   38.20
```

```
Program Name:                   DRPALL
Raw data stored on file:        S38A2
Data taken by:                  INCHECK
Tube type:                      RECTANGULAR FINNED TUBE
Fin spacing, width, height:     1.50  1.00  0.38 (mm)
Tube material:                  STAINLESS-STEEL
Thermal conductivity:            14.3 (W/m-K)
Inside diameter:                 13.08 (mm)
Root diameter:                   14.29 (mm)
Pressure condition:             ATMOSPHERIC

           Room    Inlet   Outlet   Steam    Gage   Xducer-
    Flow   Temp    Temp    Temp     Temp     Press  Press    Volts  Current
   (pct) (degC)  (degC)  (degC)   (degC)   (KPa)  (KPa)     (V)

 1   80   20.58   18.37   19.95   100.3   101.0   100.9   385.0   2.75
 2   70   20.58   18.72   20.46   100.0   100.3   100.1   385.1   2.75
 3   60   20.64   19.24   21.22   100.0   100.0    99.8   384.9   2.75
 4   50   20.65   19.22   21.51   100.2   100.7   100.9   385.0   2.75
 5   40   20.64   19.40   22.11   100.2   100.7   101.2   385.2   2.75
 6   30   20.67   19.49   22.82   100.1    99.3   100.3   385.0   2.74
 7   20   20.71   19.78   24.16    99.9    99.3   100.0   384.9   2.75
 8   20   20.70   19.79   24.17   100.0    99.1   100.0   385.1   2.75
 9   30   20.72   19.71   23.04   100.0    99.3   100.2   385.1   2.75
10   40   20.73   19.70   22.38   100.0    99.1   100.0   385.0   2.74
11   50   20.75   19.69   21.97   100.0    99.3   100.2   385.5   2.74
12   60   20.75   19.82   21.79   100.0    99.3   100.1   385.0   2.74
13   70   20.76   20.05   21.79   100.0    99.1   100.0   384.9   2.73
14   80   20.75   20.08   21.64   100.1    99.4   100.6   384.7   2.73
```

```
Program Name:                  DRPALL
Raw data stored on file:       S38A2
Data taken by:                 INCHECK
Tube type:                     RECTANGULAR FINNED TUBE
Fin spacing, width, height:    1.50  1.00  0.38 (mm)
Tube material:                 STAINLESS-STEEL
Thermal conductivity:           14.3 (W/m-K)
Inside diameter:                13.08 (mm)
Root diameter:                  14.29 (mm)
Pressure condition:            ATMOSPHERIC
System power:                   25.74 (KW)
Steam velocity:                  1.03 (m/s)
This analysis includes end-fin effect
HEATEX insert installed in tube
Enhancements based on comparison to Incheek smooth tube data

Wilson Plot regression coefficient = 1.000
Ci (based on Petukhov-Popov)       = 2.902
Alpha (based on Nusselt)           = 1.120
Enhancement (constant heat flux)   = 1.499
Enhancement (constant temp drop)   = 1.355

                          Overall     Outside     Inside
                 Coolant  Heat Xfer   Heat Xfer   Heat Xfer      Heat
                Velocity Coefficient Coefficient Coefficient     Flux       Ts-Twall
Data   LMTD        Vw        Uo          Ho          Hi           Qp          Txf
 #    (degC)    (m/s)    (W/m^2-K)   (W/m^2-K)   (W/m^2-K)    (W/m^2)      (degC)

  1    81.13    4.20    7.347E+03   1.458E+04   4.657E+04   5.961E+05    40.89
  2    80.41    3.69    7.258E+03   1.477E+04   4.191E+04   5.836E+05    39.51
  3    79.75    3.17    7.165E+03   1.510E+04   3.719E+04   5.714E+05    37.83
  4    79.81    2.66    6.976E+03   1.529E+04   3.211E+04   5.567E+05    36.41
  5    79.48    2.15    6.722E+03   1.553E+04   2.695E+04   5.343E+05    34.39
  6    78.93    1.64    6.351E+03   1.586E+04   2.156E+04   5.013E+05    31.62
  7    77.89    1.13    5.825E+03   1.676E+04   1.593E+04   4.537E+05    27.07
  8    78.02    1.13    5.823E+03   1.674E+04   1.594E+04   4.543E+05    27.14
  9    78.64    1.64    6.363E+03   1.590E+04   2.151E+04   5.004E+05    31.47
 10    78.94    2.15    6.733E+03   1.556E+04   2.704E+04   5.315E+05    34.15
 11    79.15    2.66    7.019E+03   1.546E+04   3.228E+04   5.555E+05    35.94
 12    79.17    3.17    7.185E+03   1.515E+04   3.743E+04   5.689E+05    37.54
 13    79.07    3.69    7.363E+03   1.513E+04   4.253E+04   5.822E+05    38.48
 14    79.25    4.20    7.424E+03   1.479E+04   4.746E+04   5.884E+05    39.79
Avg                                 1.547E+04               5.413E+05    35.16
```

```
Program Name:                  DRPALL
Raw data stored on file:       S48A1
Data taken by:                 INCHECK
Tube type:                     RECTANGULAR FINNED TUBE
Fin spacing, width, height:    1.50  1.00  0.48 (mm)
Tube material:                 STAINLESS-STEEL
Thermal conductivity:           14.3 (W/m-K)
Inside diameter:                13.11 (mm)
Root diameter:                  14.26 (mm)
Pressure condition:            ATMOSPHERIC

           Room     Inlet    Outlet    Steam     Gage     Xducer
    Flow   Temp     Temp     Temp      Temp      Press    Press     Volts   Current
    (pct) (degC)   (degC)   (degC)    (degC)    (KPa)    (KPa)      (V)

 1   80   20.68    18.04    19.62     100.1     100.7    100.8     384.8    2.73
 2   70   20.69    18.46    20.22     100.1     100.3    100.4     385.0    2.73
 3   60   20.68    18.82    20.81     100.0     100.0    100.0     385.1    2.73
 4   50   20.76    18.88    21.16      99.9      99.6     99.8     385.1    2.73
 5   40   20.79    19.19    21.88      99.9      98.9    100.0     385.1    2.73
 6   30   20.81    19.52    22.85      99.8      99.3    100.3     385.0    2.74
 7   20   20.82    19.40    23.79      99.9      99.3    100.3     385.1    2.74
 8   20   20.83    19.41    23.80      99.9      99.3    100.3     385.2    2.74
 9   30   20.85    19.55    22.87     100.0      99.4    100.5     385.2    2.73
10   40   20.83    19.36    22.07     100.0      99.6    100.6     385.1    2.73
11   50   20.85    19.44    21.72      99.9      99.3    100.2     385.4    2.73
12   60   20.82    19.77    21.76     100.0      99.4    100.5     384.9    2.73
13   70   20.86    19.82    21.57     100.1      99.6    100.5     384.9    2.73
14   80   20.88    19.90    21.48     100.0      99.3    100.2     384.5    2.73
```

```
Program Name:                   DRPALL
Raw data stored on file:        S48A1
Data taken by:                  INCHECK
Tube type:                      RECTANGULAR FINNED TUBE
Fin spacing, width, height:     1.50  1.00  0.48 (mm)
Tube material:                  STAINLESS-STEEL
Thermal conductivity:            14.3 (W/m-K)
Inside diameter:                 13.11 (mm)
Root diameter:                   14.26 (mm)
Pressure condition:             ATMOSPHERIC
System power:                   25.74 (KW)
Steam velocity:                  1.03 (m/s)
This analysis includes end-fin effect
HEATEX insert installed in tubs
Enhancements based on comparison to Incheck smooth tube data

Wilson Plot regression coefficient = 0.999
Ci (based on Petukhov-Popov)       = 2.852
Alpha (based on Nusselt)           = 1.108
Enhancement (constant heat flux)   = 1.479
Enhancement (constant temp drop)   = 1.341

                      Overall     Outside     Inside
             Coolant  Heat Xfer   Heat Xfer   Heat Xfer      Heat
            Velocity Coefficient Coefficient Coefficient     Flux       Ts-Twall
Data   LMTD     Vw.       Uo          Ho          Hi          Qp          Txf
 #   (degC)   (m/s)   (W/m^2-K)   (W/m^2-K)   (W/m^2-K)    (W/m^2)      (degC)

  1   81.29    4.18   7.357E+03   1.425E+04   4.639E+04   5.981E+05    41.98
  2   80.75    3.67   7.304E+03   1.458E+04   4.089E+04   5.898E+05    40.44
  3   80.14    3.16   7.175E+03   1.479E+04   3.622E+04   5.750E+05    38.89
  4   79.88    2.65   6.965E+03   1.489E+04   3.130E+04   5.564E+05    37.37
  5   79.36    2.14   6.703E+03   1.509E+04   2.631E+04   5.320E+05    35.25
  6   78.65    1.63   6.392E+03   1.576E+04   2.110E+04   5.027E+05    31.90
  7   78.30    1.12   5.824E+03   1.653E+04   1.552E+04   4.561E+05    27.58
  8   78.26    1.12   5.824E+03   1.653E+04   1.553E+04   4.558E+05    27.58
  9   78.74    1.63   6.362E+03   1.557E+04   2.111E+04   5.009E+05    32.17
 10   79.29    2.14   6.759E+03   1.536E+04   2.636E+04   5.359E+05    34.89
 11   79.32    2.65   7.006E+03   1.503E+04   3.149E+04   5.557E+05    36.98
 12   79.21    3.16   7.275E+03   1.514E+04   3.661E+04   5.763E+05    38.05
 13   79.39    3.67   7.390E+03   1.484E+04   4.151E+04   5.867E+05    39.52
 14   79.36    4.18   7.493E+03   1.466E+04   4.635E+04   5.947E+05    40.56
Avg                               1.522E+04               5.440E+05    35.94
```

```
Program Name:                    DRPALL
Raw data stored on file:         S48A2
Data taken by:                   INCHECK
Tube type:                       RECTANGULAR FINNED TUBE
Fin spacing, width, height:      1.50  1.00  0.48 (mm)
Tube material:                   STAINLESS-STEEL
Thermal conductivity:             14.3 (W/m-K)
Inside diameter:                  13.11 (mm)
Root diameter:                    14.26 (mm)
Pressure condition:              ATMOSPHERIC

              Room    Inlet   Outlet   Steam    Gage   Xducer
       Flow   Temp    Temp    Temp     Temp     Press  Press    Volts  Current
      (pct) (degC)  (degC)  (degC)   (degC)   (KPa)  (KPa)     (V)

  1    80   20.76   18.35   19.96   100.1   100.4   100.6   385.0   2.74
  2    70   20.78   18.71   20.49   100.0   100.1   100.6   385.2   2.75
  3    60   20.77   19.00   21.02   100.1    99.3   100.3   385.1   2.75
  4    50   20.70   18.99   21.31    99.9    98.6    99.7   385.1   2.75
  5    40   20.72   19.11   21.86   100.0    99.4   100.5   385.1   2.74
  6    30   20.74   19.39   22.76   100.1    99.6   100.5   384.9   2.74
  7    20   20.78   19.43   23.87   100.2   100.0   101.0   384.9   2.74
  8    20   20.79   19.51   23.94   100.1    99.8   100.8   385.0   2.75
  9    30   20.78   19.37   22.75    99.9    99.1    99.9   385.0   2.74
 10    40   20.78   19.35   22.08   100.0    98.9   100.1   384.9   2.75
 11    50   20.79   19.42   21.74   100.1    99.4   100.4   384.9   2.75
 12    60   20.87   19.61   21.61    99.9    98.7    99.7   385.3   2.75
 13    70   20.83   19.86   21.63    99.9    99.3   100.2   385.1   2.75
 14    80   20.84   19.89   21.49    99.9    99.3   100.1   385.1   2.75
```

```
          Program Name:                DRPALL
          Raw data stored on file:     S48A2
          Data taken by:               INCHECK
          Tube type:                   RECTANGULAR FINNED TUBE
          Fin spacing, width, height:  1.50  1.00  0.48 (mm)
          Tube material:               STAINLESS-STEEL
          Thermal conductivity:         14.3 (W/m-K)
          Inside diameter:              13.11 (mm)
          Root diameter:                14.26 (mm)
          Pressure condition:          ATMOSPHERIC
          System power:                 25.74 (KW)
          Steam velocity:                1.03 (m/s)
          This analysis includes end-fin effect
          HEATEX insert installed in tube
          Enhancements based on comparison to Incheck smooth tube data

          Wilson Plot regression coefficient = 0.999
          Ci (based on Petukhov-Popov)       = 2.818
          Alpha (based on Nusselt)           = 1.142
          Enhancement (constant heat flux)   = 1.538
          Enhancement (constant temp drop)   = 1.381

                              Overall     Outside     Inside
                    Coolant  Heat Xfer   Heat Xfer   Heat Xfer     Heat
                   Velocity Coefficient Coefficient Coefficient    Flux      Ts-Twall
Data   LMTD         Vw         Uo          Ho          Hi           Qp         Txf
 #    (degC)      (m/s)   (W/m^2-K)   (W/m^2-K)   (W/m^2-K)     (W/m^2)     (degC)

 1    80.94       4.18    7.510E+03   1.488E+04   4.502E+04   6.079E+05    40.86
 2    80.37       3.67    7.440E+03   1.519E+04   4.052E+04   5.979E+05    39.35
 3    80.06       3.16    7.308E+03   1.543E+04   3.587E+04   5.851E+05    37.91
 4    79.78       2.65    7.076E+03   1.549E+04   3.097E+04   5.646E+05    36.44
 5    79.56       2.14    6.821E+03   1.583E+04   2.598E+04   5.427E+05    34.23
 6    78.98       1.63    6.426E+03   1.614E+04   2.083E+04   5.075E+05    31.45
 7    78.54       1.12    5.870E+03   1.714E+04   1.535E+04   4.610E+05    26.90
 8    78.32       1.12    5.878E+03   1.718E+04   1.536E+04   4.604E+05    26.78
 9    78.80       1.63    6.474E+03   1.645E+04   2.082E+04   5.102E+05    31.02
10    79.24       2.14    6.803E+03   1.571E+04   2.604E+04   5.391E+05    34.32
11    79.51       2.65    7.144E+03   1.578E+04   3.112E+04   5.681E+05    36.00
12    79.28       3.16    7.335E+03   1.550E+04   3.611E+04   5.816E+05    37.51
13    79.20       3.67    7.498E+03   1.536E+04   4.104E+04   5.938E+05    38.67
14    79.27       4.18    7.590E+03   1.510E+04   4.579E+04   6.017E+05    39.84
Avg                                   1.580E+04               5.515E+05    35.10
```

```
          Program Name:                 DRPALL
          Raw data stored on file:      S75A1
          Data taken by:                INCHECK
          Tube type:                    RECTANGULAR FINNED TUBE
          Fin spacing, width, height:   1.50  1.00  0.75 (mm)
          Tube material:                STAINLESS-STEEL
          Thermal conductivity:          14.3 (W/m-K)
          Inside diameter:               13.10 (mm)
          Root diameter:                 14.25 (mm)
          Pressure condition:           ATMOSPHERIC

             Room    Inlet   Outlet   Steam    Gage    Xducer
      Flow   Temp    Temp    Temp     Temp     Press   Press    Volts   Current
     (pct) (degC)  (degC)  (degC)   (degC)   (KPa)   (KPa)     (V)

  1    80   22.10   20.71   22.19    100.3    101.4   101.3    384.6    2.75
  2    70   22.06   21.09   22.72    100.0    100.7   100.6    385.0    2.75
  3    60   22.21   21.35   23.20    100.3    101.0   101.1    384.8    2.76
  4    50   21.85   21.40   23.53    100.0    100.7   100.8    385.2    2.76
  5    40   21.67   21.64   24.13    100.0    100.9   101.0    384.6    2.76
  6    30   21.68   21.73   24.82    100.2    101.4   101.3    385.0    2.76
  7    20   21.65   21.58   25.66    100.1    100.7   100.8    384.8    2.76
  8    20   21.60   21.56   25.64    100.1    100.6   100.6    385.1    2.76
  9    30   21.59   21.75   24.83    100.2    100.7   100.8    385.0    2.76
 10    40   21.64   21.69   24.19    100.1    100.7   100.6    384.6    2.76
 11    50   21.65   21.72   23.85    100.2    100.7   100.9    385.1    2.76
 12    60   21.53   21.92   23.76    100.2    100.7   100.7    385.1    2.74
 13    70   21.54   21.98   23.61    100.2    100.7   100.7    385.2    2.75
 14    80   21.55   22.05   23.52    100.4    101.6   101.6    385.0    2.75
```

```
Program Name:                  DRPALL
Raw data stored on file:       S75A1
Data taken by:                 INCHECK
Tube type:                     RECTANGULAR FINNED TUBE
Fin spacing, width, height:    1.50  1.00  0.75 (mm)
Tube material:                 STAINLESS-STEEL
Thermal conductivity:           14.3 (W/m-K)
Inside diameter:                13.10 (mm)
Root diameter:                  14.25 (mm)
Pressure condition:            ATMOSPHERIC
System power:                   25.73 (KW)
Steam velocity:                  1.03 (m/s)
This analysis includes end-fin effect
HEATEX insert installed in tube
Enhancements based on comparison to Incheck smooth tube data

Wilson Plot regression coefficient = 0.999
Ci (based on Petukhov-Popov)       = 2.605
Alpha (based on Nusselt)           = 1.033
Enhancement (constant heat flux)   = 1.346
Enhancement (constant temp drop)   = 1.249

                        Overall     Outside      Inside
              Coolant  Heat Xfer   Heat Xfer   Heat Xfer      Heat
              Velocity Coefficient Coefficient Coefficient    Flux      Ts-Twall
Data   LMTD      Vw        Uo          Ho          Hi          Qp          Txf
  #   (degC)   (m/s)   (W/m^2-K)   (W/m^2-K)   (W/m^2-K)    (W/m^2)     (degC)

  1    78.87    4.19   7.047E+03   1.338E+04   4.275E+04   5.558E+05    41.52
  2    78.08    3.68   6.991E+03   1.369E+04   3.847E+04   5.459E+05    39.87
  3    77.89    3.16   6.861E+03   1.387E+04   3.404E+04   5.351E+05    38.59
  4    77.55    2.65   6.701E+03   1.416E+04   2.941E+04   5.196E+05    36.70
  5    77.09    2.14   6.394E+03   1.413E+04   2.469E+04   4.929E+05    34.90
  6    76.94    1.63   6.065E+03   1.462E+04   1.975E+04   4.666E+05    31.92
  7    76.47    1.12   5.543E+03   1.552E+04   1.452E+04   4.239E+05    27.30
  8    76.50    1.12   5.534E+03   1.546E+04   1.451E+04   4.234E+05    27.39
  9    76.92    1.63   6.051E+03   1.453E+04   1.875E+04   4.654E+05    32.03
 10    77.20    2.14   6.397E+03   1.414E+04   2.470E+04   4.939E+05    34.93
 11    77.44    2.65   6.703E+03   1.415E+04   2.951E+04   5.191E+05    36.69
 12    77.36    3.16   6.901E+03   1.399E+04   3.424E+04   5.338E+05    38.14
 13    77.39    3.68   7.024E+03   1.377E+04   3.884E+04   5.436E+05    39.48
 14    77.59    4.19   7.139E+03   1.366E+04   4.336E+04   5.540E+05    40.56
Avg                                1.422E+04               5.052E+05    35.72
```

```
        Program Name:                    DRPALL
        Raw data stored on file:         S75A2
        Data taken by:                   INCHECK
        Tube type:                       RECTANGULAR FINNED TUBE
        Fin spacing, width, height:      1.50  1.00  0.75 (mm)
        Tube material:                   STAINLESS-STEEL
        Thermal conductivity:             14.3 (W/m-K)
        Inside diameter:                  13.10 (mm)
        Root diameter:                    14.25 (mm)
        Pressure condition:              ATMOSPHERIC

           Room    Inlet   Outlet   Steam    Gage    Xducer
    Flow   Temp    Temp    Temp     Temp     Press   Press    Volts   Current
   (pct) (degC)  (degC)  (degC)   (degC)   (KPa)   (KPa)     (V)

  1  80   20.33   18.77   20.29   100.1    101.4   100.4    384.8    2.74
  2  70   20.33   19.30   20.98   100.0    102.0   101.0    385.0    2.75
  3  60   20.88   19.73   21.62   100.0    101.2   100.3    384.9    2.75
  4  50   20.42   20.03   22.20    99.9    100.3   100.2    384.9    2.74
  5  40   20.26   20.27   22.82    99.6     99.6    99.8    385.5    2.76
  6  30   20.44   20.63   23.77    99.8     99.8   100.0    385.3    2.76
  7  20   20.58   20.48   24.62    99.8    100.3   100.6    385.2    2.76
  8  20   20.47   20.49   24.54    99.6    100.2   100.6    385.2    2.76
  9  30   20.44   20.82   23.96   100.0    100.8   101.1    385.4    2.76
 10  40   20.24   20.88   23.44    99.8    101.0   101.3    384.9    2.76
 11  50   20.41   20.94   23.10    99.7    100.7   101.0    385.0    2.75
 12  60   20.30   20.98   22.88    99.7    100.7   101.1    384.8    2.75
 13  70   20.29   21.30   22.95    99.8    100.7   100.6    384.5    2.75
 14  80   20.26   21.53   23.01    99.8     99.3    99.6    385.1    2.75
```

```
    Program Name:                     DRPALL
    Raw data stored on file:          S75A2
    Data taken by:                    INCHECK
    Tube type:                        RECTANGULAR FINNED TUBE
    Fin spacing, width, height:       1.50  1.00  0.75 (mm)
    Tube material:                    STAINLESS-STEEL
    Thermal conductivity:              14.3 (W/m-K)
    Inside diameter:                   13.10 (mm)
    Root diameter:                     14.25 (mm)
    Pressure condition:               ATMOSPHERIC
    System power:                      25.74 (KW)
    Steam velocity:                     1.04 (m/s)
    This analysis includes end-fin effect
    HEATEX insert installed in tube
    Enhancements based on comparison to Incheck smooth tube data

    Wilson Plot regression coefficient = 0.999
    Ci (based on Petukhov-Popov)       = 2.850
    Alpha (based on Nusselt)           = 1.053
    Enhancement (constant heat flux)   = 1.320
    Enhancement (constant temp drop)   = 1.273

                         Overall      Outside      Inside
                Coolant  Heat Xfer    Heat Xfer    Heat Xfer      Heat
                Velocity Coefficient  Coefficient  Coefficient    Flux       Ts-Twall
Data   LMTD      Vw        Uo           Ho           Hi            Qp          Txf
 #    (degC)   (m/s)    (W/m^2-K)    (W/m^2-K)    (W/m^2-K)      (W/m^2)     (degC)

 1    80.58    4.19     7.118E+03    1.366E+04    4.258E+04     5.736E+05    41.98
 2    79.90    3.68     7.036E+03    1.388E+04    3.839E+04     5.622E+05    40.52
 3    79.37    3.16     6.884E+03    1.396E+04    3.403E+04     5.463E+05    39.13
 4    78.79    2.65     6.726E+03    1.426E+04    2.948E+04     5.300E+05    37.17
 5    78.09    2.14     6.467E+03    1.446E+04    2.476E+04     5.050E+05    34.92
 6    77.59    1.63     6.115E+03    1.484E+04    1.986E+04     4.744E+05    31.97
 7    77.19    1.12     5.570E+03    1.564E+04    1.460E+04     4.300E+05    27.50
 8    77.03    1.12     5.595E+03    1.584E+04    1.460E+04     4.310E+05    27.21
 9    77.55    1.63     6.107E+03    1.477E+04    1.990E+04     4.736E+05    32.05
10    77.64    2.14     6.506E+03    1.460E+04    2.492E+04     5.051E+05    34.60
11    77.70    2.65     6.787E+03    1.446E+04    2.978E+04     5.274E+05    36.48
12    77.82    3.16     6.996E+03    1.434E+04    3.450E+04     5.444E+05    37.95
13    77.72    3.68     7.082E+03    1.394E+04    3.924E+04     5.504E+05    39.49
14    77.54    4.19     7.197E+03    1.381E+04    4.387E+04     5.580E+05    40.40
Avg                                  1.446E+04                  5.151E+05    35.81
```

```
Program Name:                     DRPALL
Raw data stored on file:          S95A1
Data taken by:                    INCHECK
Tube type:                        RECTANGULAR FINNED TUBE
Fin spacing, width, height:       1.50  1.00  0.95 (mm)
Tube material:                    STAINLESS-STEEL
Thermal conductivity:              14.3 (W/m-K)
Inside diameter:                   13.08 (mm)
Root diameter:                     14.24 (mm)
Pressure condition:               ATMOSPHERIC

              Room    Inlet   Outlet   Steam    Gage    Xducer
       Flow   Temp    Temp    Temp     Temp     Press   Press    Volts   Current
      (pct) (degC)  (degC)  (degC)   (degC)   (KPa)   (KPa)     (V)

  1    80    23.11   19.93   21.37     99.8   100.3   100.0    384.8    2.76
  2    70    23.04   20.27   21.88    100.0   101.4   101.1    384.5    2.76
  3    60    23.14   20.59   22.41    100.1   101.4   100.8    384.6    2.77
  4    50    23.13   20.63   22.77    100.2   101.4   101.3    385.1    2.76
  5    40    23.06   20.92   23.36     99.7    99.4   100.2    384.5    2.76
  6    30    23.12   21.18   24.18    100.0   100.0   100.8    384.7    2.76
  7    20    23.11   21.02   25.00    100.0   100.5   101.3    384.9    2.76
  8    20    23.15   21.04   25.01    100.0   100.5   101.4    385.0    2.76
  9    30    23.15   21.30   24.32    100.0   100.0   100.7    385.1    2.76
 10    40    23.56   21.27   23.72    100.0    99.7   100.7    384.8    2.76
 11    50    22.29   21.35   23.44    100.0   100.0   100.9    384.8    2.76
 12    60    22.28   21.37   23.18     99.8    99.3   100.4    385.0    2.76
 13    70    22.12   21.72   23.32     99.9   100.0   100.8    384.9    2.76
 14    80    22.07   21.87   23.31    100.1   100.0   100.8    385.2    2.76
```

```
Program Name:                  DRPALL
Raw data stored on file:       S95A1
Data taken by:                 INCHECK
Tube type:                     RECTANGULAR FINNED TUBE
Fin spacing, width, height:  1.50  1.00  0.95 (mm)
Tube material:                 STAINLESS-STEEL
Thermal conductivity:           14.3 (W/m-K)
Inside diameter:                13.08 (mm)
Root diameter:                  14.24 (mm)
Pressure condition:            ATMOSPHERIC
System power:                   25.71 (KW)
Steam velocity:                  1.03 (m/s)
This analysis includes end-fin effect
HEATEX insert installed in tube
Enhancements based on comparison to Incheck smooth tube data

Wilson Plot regression coefficient = 0.998
Ci (based on Petukhov-Popov)       = 2.457
Alpha (based on Nusselt)           = 1.016
Enhancement (constant heat flux)   = 1.315
Enhancement (constant temp drop)   = 1.228

                         Overall     Outside      Inside
               Coolant  Heat Xfer   Heat Xfer    Heat Xfer      Heat
              Velocity Coefficient Coefficient Coefficient      Flux        Ts-Twall
Data   LMTD      Vw        Uo          Ho           Hi           Qp           Txf
  #   (degC)   (m/s)   (W/m^2-K)   (W/m^2-K)    (W/m^2-K)    (W/m^2)      (degC)

  1    79.12    4.20   6.870E+03   1.309E+04    4.024E+04   5.436E+05     41.52
  2    78.93    3.69   6.785E+03   1.329E+04    3.621E+04   5.355E+05     40.29
  3    78.62    3.17   6.671E+03   1.353E+04    3.206E+04   5.245E+05     38.76
  4    78.50    2.66   6.492E+03   1.374E+04    2.771E+04   5.096E+05     37.08
  5    77.56    2.15   6.236E+03   1.395E+04    2.326E+04   4.836E+05     34.67
  6    77.31    1.64   5.871E+03   1.424E+04    1.863E+04   4.539E+05     31.86
  7    76.96    1.13   5.367E+03   1.528E+04    1.370E+04   4.131E+05     27.04
  8    76.99    1.13   5.365E+03   1.525E+04    1.370E+04   4.130E+05     27.08
  9    77.15    1.64   5.916E+03   1.450E+04    1.868E+04   4.564E+05     31.48
 10    77.47    2.15   6.248E+03   1.398E+04    2.335E+04   4.840E+05     34.62
 11    77.61    2.66   6.552E+03   1.396E+04    2.791E+04   5.085E+05     36.43
 12    77.52    3.17   6.757E+03   1.384E+04    3.233E+04   5.239E+05     37.85
 13    77.44    3.69   6.914E+03   1.371E+04    3.678E+04   5.354E+05     39.05
 14    77.54    4.20   7.015E+03   1.352E+04    4.109E+04   5.439E+05     40.22
Avg                                1.399E+04                 4.949E+05     35.57
```

```
Program Name:                     DRPALL
Raw data stored on file:          S95A2
Data taken by:                    INCHECK
Tube type:                        RECTANGULAR FINNED TUBE
Fin spacing, width, height:       1.50  1.00  0.95 (mm)
Tube material:                    STAINLESS-STEEL
Thermal conductivity:              14.3 (W/m-K)
Inside diameter:                   13.08 (mm)
Root diameter:                     14.24 (mm)
Pressure condition:               ATMOSPHERIC

              Room     Inlet    Outlet    Steam     Gage     Xducer
      Flow    Temp     Temp     Temp      Temp      Press    Press     Volts    Current
     (pct)   (degC)   (degC)   (degC)    (degC)    (KPa)    (KPa)      (V)
 
  1   80     21.46    19.40    20.88     100.1     102.0    101.6     385.2    2.74
  2   70     21.41    19.70    21.35     100.0     101.4    100.8     385.0    2.74
  3   60     21.45    20.03    21.89     100.1     102.0    101.2     385.1    2.75
  4   50     21.51    20.05    22.20     100.0     101.4    101.1     385.1    2.75
  5   40     21.53    20.34    22.88      99.9     101.7    101.3     384.8    2.75
  6   30     21.50    20.60    23.70     100.0     101.4    101.2     384.9    2.76
  7   20     21.51    20.93    24.99     100.1     100.7    100.9     385.3    2.75
  8   20     21.46    20.55    24.62     100.1     100.7    100.9     385.2    2.75
  9   30     21.58    20.94    23.94     100.0     100.4    100.9     385.0    2.75
 10   40     21.48    20.94    23.35     100.1     100.6    101.3     385.1    2.75
 11   50     21.46    20.84    22.98     100.2     100.3    101.0     385.0    2.75
 12   60     21.48    21.09    22.94     100.1     100.1    100.8     384.7    2.75
 13   70     21.35    21.14    22.78     100.0     100.3    101.0     385.2    2.75
 14   80     21.41    21.17    22.64      99.9     100.0    100.5     385.2    2.75
```

```
Program Name:                  DRPALL
Raw data stored on file:       S85A2
Data taken by:                 INCHECK.
Tube type:                     RECTANGULAR FINNED TUBE
Fin spacing, width, height:    1.50  1.00  0.85 (mm)
Tube material:                 STAINLESS-STEEL
Thermal conductivity:           14.3 (W/m-K)
Inside diameter:                12.08 (mm)
Root diameter:                  14.24 (mm)
Pressure condition:            ATMOSPHERIC
System power:                   25.74 (KW)
Steam velocity:                  1.03 (m/s)
This analysis includes end-fin effect
HEATEX insert installed in tube
Enhancements based on comparison to Incheck smooth tube data

Wilson Plot regression coefficient = 1.000
Ci (based on Petukhov-Popov)       = 2.547
Alpha (based on Nusselt)           = 1.042
Enhancement (constant heat flux)   = 1.361
Enhancement (constant temp drop)   = 1.280

                      Overall     Outside      Inside
              Coolant Heat Xfer   Heat Xfer    Heat Xfer      Heat
             Velocity Coefficient Coefficient Coefficient     Flux      Ts-Twall
Data   LMTD     Vw        Uo          Ho          Hi           Qp         Txf
 #   (degC)   (m/s)   (W/m^2-K)   (W/m^2-K)   (W/m^2-K)    (W/m^2)     (degC)

  1   80.01    4.20   6.988E+03   1.340E+04   4.131E+04   5.591E+05    41.72
  2   79.44    3.69   6.943E+03   1.377E+04   3.716E+04   5.515E+05    40.07
  3   79.17    3.17   6.825E+03   1.401E+04   3.290E+04   5.403E+05    38.57
  4   78.93    2.66   6.649E+03   1.426E+04   2.841E+04   5.247E+05    36.79
  5   78.31    2.15   6.409E+03   1.458E+04   2.387E+04   5.019E+05    34.39
  6   77.85    1.64   6.017E+03   1.481E+04   1.913E+04   4.695E+05    31.64
  7   77.12    1.13   5.479E+03   1.561E+04   1.413E+04   4.226E+05    27.07
  8   77.48    1.13   5.453E+03   1.548E+04   1.407E+04   4.225E+05    27.30
  9   77.61    1.64   6.032E+03   1.468E+04   1.918E+04   4.681E+05    31.49
 10   77.98    2.15   6.358E+03   1.433E+04   2.400E+04   4.966E+05    34.65
 11   78.30    2.66   6.551E+03   1.421E+04   2.866E+04   5.208E+05    36.65
 12   78.10    3.17   6.843E+03   1.401E+04   3.328E+04   5.344E+05    38.14
 13   78.04    3.69   6.989E+03   1.386E+04   3.774E+04   5.454E+05    39.35
 14   78.04    4.20   7.106E+03   1.375E+04   4.211E+04   5.546E+05    40.33
Avg                               1.435E+04               5.079E+05    35.56
```

```
          Program Name:                 DRPALL
          Raw data stored on file:      S126A2
          Data taken by:                INCHECK
          Tube type:                    RECTANGULAR FINNED TUBE
          Fin spacing, width, height:   1.50  1.00  1.26 (mm)
          Tube material:                STAINLESS-STEEL
          Thermal conductivity:          14.3 (W/m-K)
          Inside diameter:               13.08 (mm)
          Root diameter:                 14.21 (mm)
          Pressure condition:           ATMOSPHERIC

             Room     Inlet   Outlet    Steam     Gage    Xducer
      Flow  Temp      Temp     Temp     Temp     Press    Press    Volts   Current
     (pct) (degC)   (degC)   (degC)   (degC)    (KPa)    (KPa)     (V)

  1    80   21.26    20.37    21.73     99.5     98.6     98.4    384.9    2.74
  2    70   21.32    20.78    22.31    100.4    101.4    101.3    385.0    2.74
  3    60   21.18    21.09    22.80    100.1    100.7    100.4    384.7    2.74
  4    50   21.73    21.26    23.21     99.8     99.3     99.5    385.1    2.74
  5    40   21.44    21.56    23.88    100.1     99.6    100.5    384.8    2.74
  6    30   21.48    21.83    24.67    100.1     99.3    100.2    384.5    2.75
  7    20   21.43    21.78    25.51    100.1     99.4    100.4    384.7    2.74
  8    20   21.46    21.67    25.41    100.0     99.1    100.1    384.8    2.74
  9    30   21.48    21.95    24.78    100.1     99.8    100.4    385.2    2.74
 10    40   21.70    21.94    24.25    100.2    100.3    101.2    385.2    2.74
 11    50   21.61    21.94    23.89     99.8     98.6     99.6    385.2    2.74
 12    60   21.62    22.05    23.74    100.0     99.6    100.5    384.8    2.74
 13    70   21.45    22.28    23.77    100.2     99.5    100.5    384.9    2.74
 14    80   21.71    22.33    23.67    100.0     99.1     99.9    384.9    2.74
```

```
          Program Name:                 DRFALL
          Raw data stored on file:      S126A2
          Data taken by:                INCHECK
          Tube type:                    RECTANGULAR FINNED TUBE
          Fin spacing, width, height:   1.50  1.00  1.26 (mm)
          Tube material:                STAINLESS-STEEL
          Thermal conductivity:          14.3 (W/m-K)
          Inside diameter:               13.08 (mm)
          Root diameter:                 14.21 (mm)
          Pressure condition:           ATMOSPHERIC
          System power:                  25.72 (KW)
          Steam velocity:                 1.03 (m/s)
          This analysis includes end-fin effect
          HEATEX insert installed in tube
          Enhancements based on comparison to Incheck smooth tube data

          Wilson Plot regression coefficient = 1.000
          Ci (based on Petukhov-Popov)       = 2.319
          Alpha (based on Nusselt)           = 0.929
          Enhancement (constant heat flux)   = 1.468
          Enhancement (constant temp drop)   = 1.123

                               Overall      Outside      Inside
                     Coolant  Heat Xfer    Heat Xfer    Heat Xfer       Heat
                    Velocity Coefficient Coefficient  Coefficient       Flux        Ts-Twall
      Data   LMTD      Vw        Uo           Ho           Hi            Qp           Txf
       #   (degC)    (m/s)   (W/m^2-K)    (W/m^2-K)    (W/m^2-K)      (W/m^2)       (degC)

       1    78.49    4.20    6.534E+03    1.198E+04    3.799E+04    5.129E+05      42.91
       2    78.83    3.69    6.476E+03    1.224E+04    3.421E+04    5.105E+05      41.72
       3    78.15    3.17    6.337E+03    1.234E+04    3.028E+04    4.952E+05      40.13
       4    77.60    2.66    6.149E+03    1.245E+04    2.619E+04    4.771E+05      38.33
       5    77.34    2.15    5.937E+03    1.277E+04    2.200E+04    4.592E+05      35.97
       6    76.80    1.64    5.595E+03    1.307E+04    1.762E+04    4.297E+05      32.89
       7    76.43    1.13    5.075E+03    1.370E+04    1.296E+04    3.880E+05      28.33
       8    76.42    1.13    5.087E+03    1.379E+04    1.295E+04    3.887E+05      28.19
       9    76.70    1.64    5.579E+03    1.297E+04    1.764E+04    4.279E+05      33.00
      10    77.15    2.15    5.927E+03    1.260E+04    2.209E+04    4.572E+05      36.04
      11    76.94    2.66    6.175E+03    1.251E+04    2.638E+04    4.751E+05      37.37
      12    77.15    3.17    6.353E+03    1.235E+04    3.050E+04    4.901E+05      39.59
      13    77.16    3.69    6.469E+03    1.214E+04    3.478E+04    4.991E+05      41.13
      14    76.99    4.20    6.559E+03    1.198E+04    3.279E+04    5.049E+05      42.15
      Avg                                 1.264E+04                 4.854E+05      37.02
```

```
Program Name:                     ORPALL
Raw data stored on file:          S125A3
Data taken by:                    INCHECK
Tube type:                        RECTANGULAR FINNED TUBE
Fin spacing, width, height:       1.50  1.00  1.25 (mm)
Tube material:                    STAINLESS-STEEL
Thermal conductivity:              14.3 (W/m-K)
Inside diameter:                   13.08 (mm)
Root diameter:                     14.21 (mm)
Pressure condition:               ATMOSPHERIC

              Room    Inlet   Outlet   Steam    Gage   Xducer
      Flow    Temp    Temp    Temp     Temp     Press  Press    Volts  Current
     (pct) (degC)  (degC)  (degC)   (degC)   (KPa)  (KPa)     (V)

 1    80    21.81   20.23   21.63     99.5   100.0    99.7   384.9   2.74
 2    70    21.53   20.65   22.20    100.0   101.4   101.2   385.0   2.75
 3    60    21.69   21.07   22.80     99.7    99.6    99.8   385.3   2.74
 4    50    21,89   21.17   23.17    100.0   100.0   100.9   385.4   2.75
 5    40    21.88   21.39   23.74    100.2   100.0   101.0   385.1   2.74
 6    30    22.02   21.59   24.46     99.8    99.3   100.3   384.4   2.75
 7    20    21.86   21.51   25.30    100.1   100.3   101.3   384.8   2.75
 8    20    21.80   21.41   25.21    100.1   100.0   101.2   385.2   2.75
 9    30    21.79   21.67   24.54    100.1   100.0   100.8   385.0   2.75
10    40    21.90   21.81   23.97    100.2   100.3   101.2   385.2   2.75
11    50    21.86   21.70   23.66     99.5    98.2    99.2   384.7   2.75
12    60    21.86   21.68   23.40    100.2   100,1   101.0   385.2   2.75
13    70    21.76   21.97   23.49     99.8    99.3   100.2   384.9   2.75
14    80    21,77   22.04   23.41    100,0   100.1   101.0   385.2   2.75
```

```
Program Name:                  DRPALL
Raw data stored on file:       S125A3
Data taken by:                 INCHECK
Tube type:                     RECTANGULAR FINNED TUBE
Fin spacing, width, height:    1.50  1.00  1.25 (mm)
Tube material:                 STAINLESS-STEEL
Thermal conductivity:           14.3 (W/m-K)
Inside diameter:                13.09 (mm)
Root diameter:                  14.21 (mm)
Pressure condition:            ATMOSPHERIC
System power:                  25.74 (KW)
Steam velocity:                  1.03 (m/s)
This analysis includes end-fin-effect
HEATEX insert installed in tube
Enhancements based on comparison to Incheck smooth tube data

Wilson Plot regression coefficient = 0.889
Ci (based on Petukhov-Popov)       = 2.323
Alpha (based on Nusselt)           = 0.955
Enhancement (constant heat flux)   = 1.212
Enhancement (constant temp drop)   = 1.155

                    Overall     Outside     Inside
         Coolant  Heat Xfer   Heat Xfer   Heat Xfer      Heat
        Velocity Coefficient Coefficient Coefficient     Flux     Ts-Twall
Data  LMTD   Vw        Uo          Ho          Hi          Qp        Txf
  #  (degC) (m/s)  (W/m^2-K)   (W/m^2-K)   (W/m^2-K)    (W/m^2)    (degC)

  1  78.59   4.20  6.688E+03   1.250E+04   3.802E+04   5.257E+05   42.04
  2  78.56   3.69  6.605E+03   1.270E+04   3.424E+04   5.189E+05   40.86
  3  77.82   3.17  6.444E+03   1.274E+04   3.034E+04   5.015E+05   39.35
  4  77.81   2.66  6.260E+03   1.291E+04   2.622E+04   4.871E+05   37.75
  5  77.60   2.15  5.994E+03   1.303E+04   2.201E+04   4.651E+05   35.70
  6  76.74   1.64  5.663E+03   1.344E+04   1.762E+04   4.345E+05   32.33
  7  76.66   1.13  5.154E+03   1.428E+04   1.295E+04   3.951E+05   27.96
  8  76.79   1.13  5.151E+03   1.428E+04   1.294E+04   3.955E+05   27.70
  9  76.96   1.64  5.655E+03   1.339E+04   1.763E+04   4.352E+05   32.50
 10  77.44   2.15  6.020E+03   1.313E+04   2.206E+04   4.662E+05   35.50
 11  76.85   2.66  6.258E+03   1.286E+04   2.638E+04   4.810E+05   37.39
 12  77.66   3.17  6.427E+03   1.264E+04   3.053E+04   4.981E+05   39.49
 13  77.08   3.69  6.587E+03   1.256E+04   3.472E+04   5.077E+05   40.41
 14  77.29   4.20  6.684E+03   1.241E+04   3.875E+04   5.166E+05   41.64
Avg                            1.306E+04               4.735E+05   36.45
```

```
          Program Name:                 DRPALL
          Raw data stored on file:      S142A3
          Data taken by:                INCHECK
          Tube type:                    RECTANGULAR FINNED TUBE
          Fin spacing, width, height:   1.50  1.00  1.42 (mm)
          Tube material:                STAINLESS-STEEL
          Thermal conductivity:          14.3 (W/m-K)
          Inside diameter:               13.10 (mm)
          Root diameter:                 14.28 (mm)
          Pressure condition:           ATMOSPHERIC

          Room    Inlet   Outlet   Steam    Gage    Xducer
    Flow  Temp    Temp    Temp     Temp     Press   Press    Volts   Current
   (pct) (degC)  (degC)  (degC)   (degC)   (KPa)   (KPa)     (V)

 1   80   20.48   17.73   19.07   100.4    100.7   100.9    384.8    2.74
 2   70   20.49   18.02   19.50   100.0    100.0   100.0    385.1    2.74
 3   60   20.52   18.26   19.93   100.3    100.7   100.8    385.1    2.74
 4   50   20.56   18.29   20.21   100.0     99.6   100.0    385.1    2.74
 5   40   20.55   18.54   20.81   100.0     99.3   100.1    384.8    2.74
 6   30   20.59   18.77   21.58   100.1     99.3   100.4    385.2    2.74
 7   20   20.58   18.60   22.32   100.0     98.8    99.9    384.8    2.74
 8   20   20.57   18.60   22.32    99.9     98.9   100.0    384.7    2.74
 9   30   20.58   18.84   21.63    99.9     99.7    99.9    385.2    2.74
10   40   20.62   18.69   20.95    99.8     98.6    99.7    385.1    2.74
11   50   20.60   18.69   20.60   100.1     99.6   100.8    384.9    2.74
12   60   20.60   18.92   20.57    99.9     98.6    99.6    384.8    2.74
13   70   20.60   18.98   20.44   100.0     98.8    99.9    385.0    2.74
14   80   20.59   19.04   20.35    99.9     99.1   100.3    385.0    2.74
```

```
Program Name:                    DRPALL
Raw data stored on file:         S142A3
Data taken by:                   INCHECK
Tube type:                       RECTANGULAR FINNED TUBE
Fin spacing, width, height:      1.50  1.00  1.42 (mm)
Tube material:                   STAINLESS-STEEL
Thermal conductivity:            14.3 (W/m-K)
Inside diameter:                  13.10 (mm)
Root diameter:                    14.28 (mm)
Pressure condition:              ATMOSPHERIC
System power:                     25.73 (KW)
Steam velocity:                    1.03 (m/s)
This analysis includes end-fin effect
HEATEX insert installed in tube
Enhancements based on comparison to Incheck smooth tube data

Wilson Plot regression coefficient = 1.000
Ci (based on Petukhov-Popov)       = 2.433
Alpha (based on Nusselt)           = 0.861
Enhancement (constant heat flux)   = 1.055
Enhancement (constant temp drop)   = 1.041

                          Overall     Outside      Inside
               Coolant   Heat Xfer   Heat Xfer   Heat Xfer      Heat
              Velocity Coefficient Coefficient Coefficient      Flux      Ts-Twall
Data   LMTD      Vw         Uo          Ho          Hi           Qp          Txf
  #   (degC)   (m/s)    (W/m^2-K)   (W/m^2-K)   (W/m^2-K)     (W/m^2)      (degC)

  1    81.98    4.19    6.134E+03   1.088E+04   3.860E+04    5.028E+05    46.22
  2    81.26    3.68    6.054E+03   1.099E+04   3.471E+04    4.919E+05    44.75
  3    81.17    3.16    5.914E+03   1.101E+04   3.070E+04    4.800E+05    43.59
  4    80.75    2.65    5.792E+03   1.126E+04   2.651E+04    4.677E+05    41.54
  5    80.36    2.14    5.581E+03   1.141E+04   2.226E+04    4.485E+05    39.29
  6    79.89    1.63    5.290E+03   1.170E+04   1.783E+04    4.226E+05    36.12
  7    79.56    1.12    4.843E+03   1.232E+04   1.310E+04    3.853E+05    31.29
  8    79.41    1.12    4.860E+03   1.242E+04   1.310E+04    3.859E+05    31.06
  9    79.62    1.63    5.290E+03   1.159E+04   1.784E+04    4.211E+05    36.02
 10    80.01    2.14    5.571E+03   1.136E+04   2.230E+04    4.457E+05    39.23
 11    80.50    2.65    5.804E+03   1.128E+04   2.663E+04    4.672E+05    41.42
 12    80.12    3.15    5.957E+03   1.113E+04   3.093E+04    4.773E+05    42.88
 13    80.28    3.88    6.046E+03   1.093E+04   3.508E+04    4.854E+05    44.41
 14    80.23    4.19    6.164E+03   1.093E+04   3.917E+04    4.945E+05    45.27
Avg                                 1.138E+04                4.554E+05    40.22
```

```
          Program Name:                    DRPALL
          Raw data stored on file:         S142A4
          Data taken by:                   INCHECK
          Tube type:                       RECTANGULAR FINNED TUBE
          Fin spacing, width, height:      1.50  1.00  1.42 (mm)
          Tube material:                   STAINLESS-STEEL
          Thermal conductivity:             14.3 (W/m-K)
          Inside diameter:                  13.10 (mm)
          Root diameter:                    14.28 (mm)
          Pressure condition:              ATMOSPHERIC

               Room    Inlet   Outlet   Steam    Gage   Xducer
        Flow   Temp    Temp    Temp     Temp     Press  Press    Volts  Current
       (pct) (degC)  (degC)  (degC)   (degC)   (KPa)  (KPa)     (V)

   1    80   20.02   17.11   18.46    100.2   100.7   100.4   385.1   2.76
   2    70   20.03   17.41   18.90    100.2   100.7   100.2   384.9   2.76
   3    60   20.04   17.67   19.36    100.1   100.7   100.4   385.1   2.76
   4    50   20.07   17.66   19.61    100.1   100.9   100.4   384.9   2.75
   5    40   20.09   17.85   20.13     99.8   100.0    99.6   385.1   2.76
   6    30   20.08   18.02   20.87    100.3   101.4   101.3   384.9   2.76
   7    20   20.11   18.22   21.98    100.2   100.7   101.1   385.3   2.76
   8    20   20.11   18.20   21.96    100.2   100.7   101.2   385.0   2.76
   9    30   20.14   18.22   21.05    100.1   100.1   100.7   385.1   2.76
  10    40   20.14   18.22   20.51    100.1   100.3   100.9   385.0   2.76
  11    50   20.16   18.34   20.25    100.0    99.8   100.4   385.0   2.76
  12    60   20.17   18.39   20.06    100.1   100.0   100.4   385.1   2.76
  13    70   20.20   18.70   20.16    100.0   100.0   100.3   385.0   2.76
  14    80   20.20   18.76   20.08    100.3   100.7   101.1   385.0   2.76
```

```
Program Name:                  DRPALL
Raw data stored on file:       S142A4
Data taken by:                 INCHECK
Tube type:                     RECTANGULAR FINNED TUBE
Fin spacing, width, height:    1.50  1.00  1.42 (mm)
Tube material:                 STAINLESS-STEEL
Thermal conductivity:           14.3 (W/m-K)
Inside diameter:                13.10 (mm)
Root diameter:                  14.28 (mm)
Pressure condition:            ATMOSPHERIC
System power:                   25.74 (KW)
Steam velocity:                  1.03 (m/s)
This analysis includes end-fin effect
HEATEX insert installed in tube
Enhancements based on comparison to Incheck smooth tube data

Wilson Plot regression coefficient = 0.999
Ci (based on Petukhov-Popov)       = 2.470
Alpha (based on Nusselt)           = 0.864
Enhancement (constant heat flux)   = 1.060
Enhancement (constant temp drop)   = 1.045

                          Overall     Outside      Inside
               Coolant   Heat Xfer   Heat Xfer   Heat Xfer      Heat
              Velocity Coefficient Coefficient Coefficient      Flux      Ts-Twall
Data   LMTD      Vw         Uo          Ho          Hi           Qp          Txf
  #   (degC)   (m/s)   (W/m^2-K)   (W/m^2-K)   (W/m^2-K)     (W/m^2)      (degC)

  1    82.41    4.19   6.173E+03   1.097E+04   3.860E+04   5.087E+05     46.35
  2    82.01    3.68   6.070E+03   1.102E+04   3.488E+04   4.978E+05     45.18
  3    81.60    3.16   5.983E+03   1.122E+04   3.096E+04   4.882E+05     43.52
  4    81.48    2.65   5.814E+03   1.130E+04   2.872E+04   4.737E+05     41.92
  5    80.83    2.14   5.589E+03   1.140E+04   2.242E+04   4.519E+05     39.62
  6    80.80    1.63   5.329E+03   1.183E+04   1.735E+04   4.306E+05     36.39
  7    80.06    1.12   4.871E+03   1.235E+04   1.324E+04   3.899E+05     31.55
  8    80.09    1.12   4.869E+03   1.235E+04   1.324E+04   3.900E+05     31.57
  9    80.50    1.63   5.288E+03   1.182E+04   1.799E+04   4.257E+05     36.64
 10    80.69    2.14   5.606E+03   1.145E+04   2.252E+04   4.523E+05     39.52
 11    80.71    2.65   5.779E+03   1.113E+04   2.693E+04   4.664E+05     41.90
 12    80.84    3.16   5.979E+03   1.117E+04   3.121E+04   4.833E+05     43.28
 13    80.55    3.68   6.030E+03   1.083E+04   3.553E+04   4.858E+05     44.39
 14    80.89    4.19   6.138E+03   1.081E+04   3.064E+04   4.965E+05     45.94
Avg                                1.138E+04               4.600E+05     40.59
```

```
Program Name:                    DRPALL
Raw data stored on file:         S142A5
Data taken by:                   INCHECK
Tube type:                       RECTANGULAR FINNED TUBE
Fin spacing, width, height:      1.50  1.00  1.42 (mm)
Tube material:                   STAINLESS-STEEL
Thermal conductivity:             14.3 (W/m-K)
Inside diameter:                  13.10 (mm)
Root diameter:                    14.20 (mm)
Pressure condition:              ATMOSPHERIC

           Room     Inlet   Outlet    Steam     Gage    Xducer
     Flow  Temp     Temp     Temp     Temp      Press   Press     Volts   Current
    (pct) (degC)   (degC)   (degC)   (degC)    (KPa)   (KPa)      (V)

  1   80   19.78    17.74    19.09     99.6     99.3     98.9    384.9    2.73
  2   70   19.80    17.97    19.48    100.1    100.7    100.5    385.2    2.73
  3   60   19.83    18.29    19.98     99.8    100.0     99.7    385.1    2.74
  4   50   19.82    18.23    20.18    100.0    100.1    100.4    385.0    2.75
  5   40   19.84    18.22    20.55    100.2    100.7    100.9    385.1    2.74
  6   30   19.84    18.45    21.32    100.0     99.6    100.6    385.2    2.74
  7   20   19.89    18.54    22.33    100.0     99.6    100.5    384.8    2.73
  8   20   19.89    18.52    22.31    100.1     99.4    100.5    385.0    2.73
  9   30   19.90    18.47    21.34     99.9     99.7    100.5    384.9    2.74
 10   40   19.92    18.37    20.70     99.5     98.7     99.8    385.0    2.74
 11   50   19.96    18.47    20.42    100.1     99.6    100.4    385.1    2.74
 12   60   19.92    18.55    20.24    100.0    100.0    100.9    384.7    2.74
 13   70   19.95    18.73    20.22    100.1     99.8    100.6    385.1    2.73
 14   80   19.95    18.79    20.13     99.9     99.3    100.1    385.1    2.73
```

```
Program Name:                 DRPALL
Raw data stored on file:      5142A5
Data taken by:                INCHECK
Tube type:                    RECTANGULAR FINNED TUBE
Fin spacing, width, height:   1.50  1.00  1.42 (mm)
Tube material:                STAINLESS-STEEL
Thermal conductivity:          14.3 (W/m-K)
Inside diameter:               13.10 (mm)
Root diameter:                 14.28 (mm)
Pressure condition:           ATMOSPHERIC
System power:                  26.74 (KW)
Steam velocity:                 1.03 (m/s)
This analysis includes end-fin effect
HEATEX insert installed in tube
Enhancements based on comparison to Incheck smooth tube data

Wilson Plot regression coefficient = 0.999
Ci (based on Petukhov-Popov)       = 2.475
Alpha (based on Nusselt)           = 0.886
Enhancement (constant heat flux)   = 1.096
Enhancement (constant temp drop)   = 1.071

                        Overall     Outside     Inside
              Coolant  Heat Xfer   Heat Xfer   Heat Xfer     Heat
             Velocity Coefficient Coefficient Coefficient    Flux       Ts-Twall
Data   LMTD     Vw        Uo          Ho          Hi          Qp          Txf
 #   (degC)   (m/s)   (W/m^2-K)   (W/m^2-K)   (W/m^2-K)    (W/m^2)      (degC)

 1    81.20    4.19   6.277E+03   1.128E+04   3.928E+04   5.097E+05    45.20
 2    81.37    3.68   6.175E+03   1.134E+04   3.529E+04   5.025E+05    44.32
 3    80.72    3.16   6.051E+03   1.142E+04   3.124E+04   4.884E+05    42.78
 4    80.84    2.65   5.897E+03   1.157E+04   2.695E+04   4.767E+05    41.19
 5    80.82    2.14   5.673E+03   1.172E+04   2.257E+04   4.585E+05    39.13
 6    80.12    1.63   5.384E+03   1.205E+04   1.807E+04   4.313E+05    35.80
 7    79.59    1.12   4.944E+03   1.276E+04   1.332E+04   3.935E+05    30.93
 8    79.64    1.12   4.940E+03   1.274E+04   1.331E+04   3.934E+05    30.88
 9    80.02    1.63   5.411E+03   1.218E+04   1.808E+04   4.330E+05    35.54
10    80.41    2.14   5.723E+03   1.192E+04   2.261E+04   4.602E+05    38.60
11    80.64    2.65   5.890E+03   1.153E+04   2.702E+04   4.750E+05    41.19
12    80.64    3.16   6.066E+03   1.148E+04   3.133E+04   4.892E+05    42.69
13    80.63    3.68   6.143E+03   1.120E+04   3.559E+04   4.953E+05    44.24
14    80.51    4.19   6.315E+03   1.136E+04   3.973E+04   5.084E+05    44.76
Avg                               1.175E+04               4.654E+05    39.80
```

APPENDIX E. UNCERTAINTY ANALYSIS

A. INTRODUCTION

The uncertainty in an experimental result can come from systematic errors, random errors, or a combination of both. Systematic errors are those errors that cause a measurement to be off by a fixed amount or percentage. Some causes are faulty or imprecise instrument calibration or limited system resolution. Random errors are errors whose magnitude and direction vary without pattern. Causes include fluctuating experimental conditions or insufficient instrument sensitivity. [Ref. 61]

When a calculated result is a function of several different measured variables, each having its own uncertainty, the uncertainty in the final result is a function of each of the component uncertainties. Finding the resultant uncertainty from the uncertainty of independent components is called propagation of uncertainty. Kline and McClintock [Ref. 62] formulated a method for determining uncertainty propagation if the component uncertainties are independent, relatively small, and have the same chance of occurrence. Assuming that uncertainties behave like standard deviations, they postulated that the total uncertainty (u_y) of a quantity y is related to the individual uncertainties (u_i) by

$$u_y = \sqrt{\left(\frac{\partial y}{\partial x_1}u_1\right)^2 + \left(\frac{\partial y}{\partial x_2}u_2\right)^2 + \ldots + \left(\frac{\partial y}{\partial x_n}u_n\right)^2}. \qquad \textbf{(E.1)}$$

For example, suppose

$$y = Ax_1^2x_2 + Bx_3. \qquad \textbf{(E.2)}$$

Then using equation (E.1), the overall uncertainty is

$$u_y = \sqrt{(2Ax_1x_2u_1)^2 + (Ax_1^2u_2)^2 + (Bu_3)^2}. \qquad \textbf{(E.3)}$$

At NPS, Mitrou [Ref. 30] wrote a computer program to calculate the experimental uncertainties in the heat transfer coefficients using this method for specific data points. His program was expanded in this work to find the uncertainties in the heat transfer coefficients for a complete data set and for the final quantity of interest, the enhancement.

B. UNCERTAINTIES IN THE MEASURED VARIABLES

To begin the uncertainty analysis, the uncertainties of the measured components are required. The measured uncertainties in the dimensions of the tubes (root/inside diameters and end/condensing lengths) were observed to be very small and hence are neglected. The uncertainty in the rotameter reading (u_{fm}) is taken as ±0.5 percent due to calibration uncertainty and rotameter fluctuation. The uncertainty in thermal conductivity for stainless steel (u_{km}) is estimated from the curve fit in Thermophysical Properties of Matter [Ref. 63] as ±1 W/m-K. The uncertainties in the coolant inlet (u_{Tin}) and outlet (u_{Tout}) temperatures as measured by the quartz thermometers are a function of calibration and precision uncertainties. The total is estimated as ±0.05°C [Refs. 61, 64]. Lastly, the uncertainty in the steam thermocouple measurement (u_{Tstm}) is estimated as the sum of a ±0.1°C calibration error [Ref. 61] and a precision error of ±0.1°C for vacuum runs and ±0.3°C for atmospheric runs. This precision error was introduced after noting that the two vapor-space thermocouple readings differed by up to these amounts during experimentation. The thermocouples share the same thermal well but contact slightly different portions of the well wall. The difference in their readings increases at higher temperatures where the thermal well temperature gradient is steeper. The total u_{Tstm} is then ±0.2 and ±0.4°C for vacuum and atmospheric conditions respectively. Finally, because all the thermophysical properties in the analysis are represented as polynomial expansions of temperature, their uncertainties are simply their first derivatives with respect to temperature multiplied by the uncertainty in temperature.

C. UNCERTAINTY ANALYSIS

The HP-BASIC program UNCERT is coded by combining the data reduction portion of program DRPALL with the Kline and McClintock [Ref. 62] uncertainty analysis procedure. An uncertainty is calculated for each equation in DRPALL to yield individual uncertainties for the coolant mass flow ($\dot{m}$) and velocity (v_w), inside heat transfer correlation (Ω), log-mean-temperature-difference ($LMTD$), heat flux (q''), and overall heat transfer coefficient (U_o) for each data point.

Because the inside and outside heat transfer correlation leading coefficients (C_i and C_o) are not calculated from explicit equations but rather are determined from a least-squares line fit in the modified Wilson procedure, their uncertainties are calculated by a different method [Ref. 65, p. 498]. It is assumed that the Wilson X-Y data points are normally and independently distributed. A 100(1-α) confidence (or uncertainty) interval with n-2 degrees of freedom on the slope (m) for simple linear regression is

$$\hat{m} - t_{\alpha/2,n-2}\sqrt{\frac{\hat{\sigma}^2}{S_{xx}}} \le m \le \hat{m} + t_{\alpha/2,n-2}\sqrt{\frac{\hat{\sigma}^2}{S_{xx}}}. \qquad \textbf{(E.4)}$$

Similarly, a 100(1-α) uncertainty interval on the intercept (b) is

$$\hat{b} - t_{\alpha/2,n-2}\sqrt{\hat{\sigma}^2\left(\frac{1}{n} + \frac{\overline{x}^2}{S_{xx}}\right)} \le b \le \hat{b} + t_{\alpha/2,n-2}\sqrt{\hat{\sigma}^2\left(\frac{1}{n} + \frac{\overline{x}^2}{S_{xx}}\right)}. \qquad \textbf{(E.5)}$$

For equations (E.4) and (E.5), the unbiased estimator of the variance ($\hat{\sigma}^2$) is

$$\hat{\sigma}^2 = \frac{\sum_{x=1}^{n} y_i^2 - n\overline{y}^2 + m\left(\frac{\sum_{x=1}^{n} x_i \sum_{x=1}^{n} y_i - \sum_{x=1}^{n} (x_i y_i)}{n}\right)}{n-2}, \qquad \textbf{(E.6)}$$

S_{xx} is

$$S_{xx} = \sum_{x=1}^{n} (x_i - \overline{x})^2 = \sum_{x=1}^{n} x_i^2 - \frac{\left(\sum_{x=1}^{n} x_i\right)^2}{n}, \qquad \textbf{(E.7)}$$

the mean ($\overline{x}$) is

$$\overline{x} = \sum_{x=1}^{n} x_i, \qquad \textbf{(E.8)}$$

the mean ($\overline{y}$) is

$$\overline{y} = \sum_{x=1}^{n} y_i, \qquad \textbf{(E.9)}$$

and $t_{\alpha/2,n-2}$ is found from the statistical t-distribution. C_i and C_o are the reciprocals of m and b. Following Kline and McClintock [Ref. 62], the uncertainties in C_i (u_{Ci}) and in C_o (u_{Co}) are

$$u_{C_i} = \frac{u_{slope}}{m^2}, \qquad \textbf{(E.10)}$$

and

$$u_{C_o} = \frac{u_{intercept}}{b^2}. \qquad \textbf{(E.11)}$$

The uncertainty in enhancement ($u_{\epsilon\Delta T}$) is then calculated by applying Kline and McClintock [Ref. 62] to equation (4.47) to yield

$$u_{\epsilon_{\Delta T}} = \epsilon_{\Delta T}\sqrt{\left(\frac{u_{C_{o,finned}}}{C_{o,finned}}\right)^2 + \left(\frac{u_{C_{o,smooth}}}{C_{o,smooth}}\right)^2}. \qquad \textbf{(E.12)}$$

For a 95 percent confidence interval and 14 data points (n), $\alpha/2 = 0.025$, n-2 = 12 degrees of freedom, and $t = 2.179$. In equation (E.12), $u_{Co,smooth}$ was determined by merging two smooth tube data runs for each pressure condition and using the uncertainty analysis on these merged 28 point files.

Once the uncertainties in C_i and C_o are found, the uncertainties in h_i and h_o are determined by applying Kline and McClintock's [Ref. 62] method to equations (4.18) and (4.19). The UNCERT program code and uncertainty analysis for each accepted experimental trial follow.

D. LIMITATIONS

It is important to note that u_{Ci} and u_{Co} are determined solely on the basis of the goodness-of-fit of the modified Wilson plot to the data points. For instance, if the X-Y data points lie exactly on the least-squares line, then the $\hat{\sigma}$ expression in equations (E.4) and (E.5) will be equal to zero, and the uncertainty interval will be zero. This means that if the uncertainty of the data points is large, yet the curve fit is close, u_{Ci} and u_{Co} will be small and consequently the uncertainties in h_i, h_o, and enhancement will be smaller than intuitively indicated. This analysis typically yields uncertainties in the overall heat transfer coefficient approaching 20 percent yet the uncertainties in C_i and C_o are typically only a few percent. In view of this, the analysis provides a conservative estimate of the uncertainties in h_i, h_o, and enhancement.

Another method of uncertainty analysis is also possible. The modified Wilson plot of the 0.48 mm fin height vacuum experimental trials is shown as line A in Figure E.1. The calculated value of C_o for these runs was 0.96 with an uncertainty of 3 percent as determined by the previous method. The calculated values of the uncertainty in the overall heat transfer coefficient for these trials was between 8 and 22

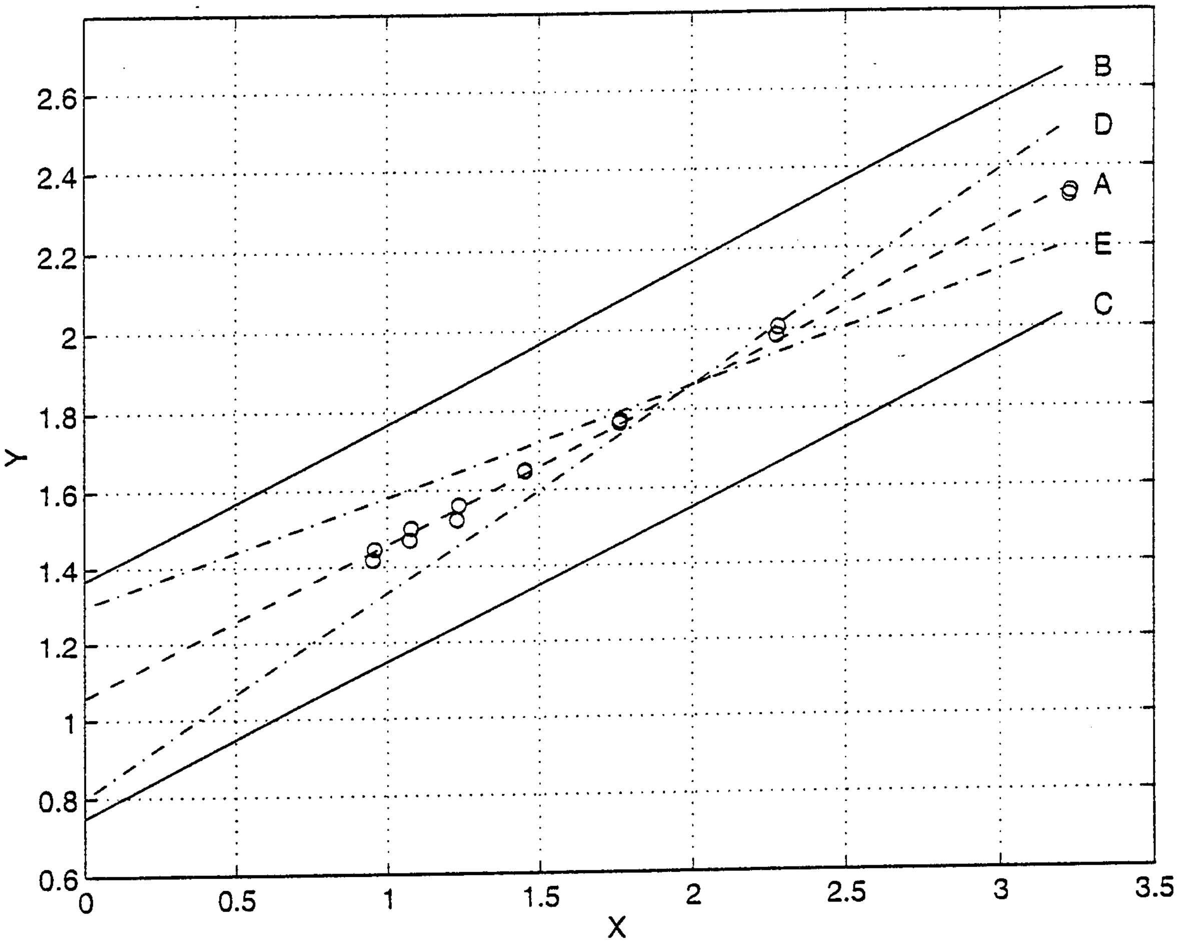

Figure E.1 Range of Uncertainty in Intercept for a Modified Wilson Plot of a Stainless Steel Integral Fin Tube with Fin Height 0.48 mm Under Vacuum Conditions

percent. The Kline and McClintock [Ref. 62] method was explicitly applied to equation (4.22) to give an uncertainty in Y as a function of the uncertainty in U_o. The limits of uncertainty in Y are shown as lines B and C. Therefore, given a value of X, any value of Y that lies between lines B and C fits the data uncertainty. If there are proportional bias errors in the data collection, there is no reason to believe that the uncertainty for each data point is the same, so the data points could just as reasonably fit lines D or E. Using the inverse of the intercepts (C_o) of lines B and C as the extreme values, $0.72 < C_o < 1.32$. This yields an uncertainty in C_o of -25 to +37 percent. Since the uncertainty in the outside heat transfer coefficient is a function of C_o, it would have a similar range. This method yields uncertainties so large, that the data is virtually useless. Obviously, another approach is needed.

```
100 ! UNCERT (GEORGE INCHECK-1994)
110 ! This program uses the Modified Wilson plot of program DRPALL and the
120 ! linearized uncorrelated coefficient-method detailed in T. Beckwith, R.
130 ! Marangoni, and J. Lienhard MECHANICAL MEASUREMENTS to calculate the
140 ! uncertainties in enhancement, heat flux, overall heat transfer coefficient
,
150 ! inside heat transfer coefficient, outside heat transfer coefficient, and
160 ! film delta-T.  The input arguments are the uncertainties in coolant
170 ! temperatures, steam temperature, rotameter reading, and tube thermal
180 ! conductivity.  The coolant temperature uncertainty was based on a quartz
190 ! thermometer calibration accuracy of 0.04 degC, precision of 0.01 degC, and
200 ! a measurement that is the average of 5 readings.  The steam temperature
210 ! uncertainty is based on a calibration accuracy of 0.1 degC, precision of
220 ! 0.1 degC for vacuum conditions or 0.3 degC for atmospheric test conditions
,
230 ! and a measurement that is the average of two thermocouple measurements,
240 ! each the average of 5 readings.  The rotameter uncertainty is based on a
250 ! calibration accuracy and precision of 0.25 percent each.  The thermal
260 ! conductivity uncertainty was based on the range of values for thermal
270 ! conductivity detailed in THERMOPHYSICAL PROPERTIES OF MATTER for the range
280 ! of tube wall temperatures expected.  Tube geometric dimensions were
290 ! assumed constant with insignificant uncertainties.
300 !
310 ! Dictionary of variables
320 ! A - Cross-sectional area of tube (m^2).
330 ! Alp - Nusselt leading coefficient.
340 ! Alpc - Iteratively determined Alp.  Compared to Alp to test for
350 !      convergence.
360 ! Alpsm - Nusselt leading coefficient for a smooth tube.
370 ! Areacorr - Tube inside x-sectional area loss due to heatex insert (m^2).
380 ! Array - An array for storing T1, T2, Md, Tsteam, and OMEGA and
390 ! their uncertainties during Wilson analysis.
400 ! Cerr - Absolute error between Ci and Cic.  Used to test convergence.
410 ! Ci - Leading coefficient in inside heat transfer correlation.
420 ! Cic - Iteratively determined Ci.  Compared to Ci to test for convergence.
430 ! Cpcw - Specific heat of cooling water (J/kg-K).
440 ! Cpf - Specific heat of condensing film (J/kg-K).
450 ! C1 - Constants in the function FNHfg.
460 ! C2 - Constants in the function FNMuw.
470 ! C3 - Constants in the function FNRhow.
480 ! C4 - Constants in the function FNKw.
490 ! C5 - Constants in the  function FNCpw.
500 ! C6 - Constants in the function FNUrho.
510 ! C7 - Constants in the function FNUcp.
520 ! C8 - Constants in the function FNUk.
530 ! C9 - Constants in the function FNUmu.
540 ! C10 - Constants in the function FNUpr.
550 ! C11 - Constants in the function FNUhfg.
```

```
560 ! Ddd - Dummy variable.
570 ! Di - Inside diameter of tube (m).
580 ! Droot - Root diameter of finned tube or O.D. of smooth tube (m).
590 ! D_file$ - Read/write data storage file.
600 ! Eq - Enhancement ratio for constant heat flux across the condensate film
610 !        for a finned tube vs smooth tube.
620 ! Et - Enhancement ratio for constant temperature drop across the condensate
630 !        film for a finned tube vs smooth tube,
640 ! Fe1 - Axial fin efficiency for tube inlet length.
650 ! Fe2 - Axial fin efficiency for tube outlet length,
660 ! Fm - Cooling water flow measured by rotameter (pct).
670 ! Hfgf - Latent heat of condensation for saturated water evaluated at film
680 !       temperature plus the effects of thermal advection (J/kg).
690 ! Hi - Inside heat transfer coefficient (W/m^2-K).
700 ! Ho - Outside heat transfer coefficient (W/m^2-K).
710 ! I - Loop counter and array subscript.
720 ! Ifg - Tube geometry flag.
730 ! Imc - Tube material flag.
740 ! Ipc - Experiment pressure flag.
750 ! J - Loop counter and array subscript.
760 ! Kcw - Thermal conductivity of cooling water (W/M-K).
770 ! Kf - Thermal conductivity of film (W/m-K).
780 ! Km - Thermal conductivity of tube metal (W/m-K).
790 ! L - Tube condensing length (m).
800 ! Lmtd - Log mean temperature difference (degK).
810 ! L1 - Tube inlet end length (m).
820 ! L2 - Tube outlet end length (m).
830 ! M - The "m" component of fin efficiency (1/m).
840 ! Md - Cooling water mass flow rate (kg/s).
850 ! Mucw - Viscosity of cooling water (kg/m-s).
860 ! Muf - Viscosity of film (kg/m-s).
870 ! New - Nusselt function for outside heat transfer on horizontal smooth tube
s.
880 ! Nrun - Number of data runs.
890 ! Ntercept - Intercept of the modified Wilson plot line.
900 ! Omega - Petukhov's Nusselt number for inside heat transfer.
910 ! P - Tube inside perimeter (m).
920 ! Ppk1 - Constant K1 in Petukhov's relation.
930 ! Ppk2 - Constant K2 in Petukhov's relation.
940 ! Pp1 - Numerator in Petukhov's relation Nu=f(Re,Pr).
950 ! Pp2 - Denominator in Petukhov's relation Nu=f(Re,Pr).
960 ! Prcw - Prandtl Number of cooling water.
970 ! P1 thru P43 - Partial derivatives of various equations used in uncertainty
980 !     determination.
990 ! Q - Heat transfer rate to coolant (W).
1000! Qp - Heat flux to coolant (J/m^2-s).
1010! Rei - Reynolds Number of cooling water through a circular pipe.
1020! Rhof - Density of film (kg/m^3).
```

```
1030! Rhocw - Density of cooling water (kg/m^3).
1040! Rm - Wall thermal resistence (K/W).
1050! Sigmahat2 - Sse/(Nrun-2).
1060! Slope - Slope of the modified Wilson plot line.
1070! Sse - Syy-Slope*Sxy.
1080! Sumx - Sum of X.
1090! Sumxy - Sum of X*Y.
1100! Sumx2 - Sum of X^2.
1110! Sumy - Sum of Y.
1120! Sumy2 - Sum of Y^2.
1130! Sxx - Sumx2-Sumx^2/Nrun.
1140! Sxy - Sumxy-Sumx*Sumy/Nrun.
1150! Syy - Sumy2-Nrun*Tbar^2.
1160! Tau - t-distribution for a two-sided 95% confidence interval.
1170! Tavg - Average cooling water temperature (degC).
1180! Tcor - Temperature rise of coolant due to viscous heating of internal
1190!        flow (degC).
1200! Temp - Temporary variable.
1210! Tfilm - Temperature of film (degC).
1220! Trise - Delta T of coolant after subtracting viscous heating effect (degC)
;
1230! Tsteam - Temperature of steam in condenser (degC).
1240! Two - Tube outside wall temperature (degC).
1250! Twoc - Iteratively obtained wall temp.  Compared to Two for convergence.
1260! Txf - Temperature drop across the condensate film (degC).
1270! T1 - Coolant inlet temperature as measured by qtz thermometer (degC).
1280! T2 - Coolant outlet temperature as measured by qtz thermometer(degC).
1290! Ualp - Uncertainty in Alp.
1300! Ualpsm - Uncertainty in Alpsm.
1310! Uci - Uncertainty in Ci.
1320! Ucp - Uncertainty in coolant specific heat.
1330! Ueq - Uncertainty in Eq.
1340! Uet - Uncertainty in Et.
1350! Ufe1 - Uncertainty in Fe1.
1360! Ufe2 - Uncertainty in Fe2.
1370! Ufm - Uncertainty in flowmeter reading.
1380! Uhfg - Uncertainty in latent heat of vaporization.
1390! Uhi - Uncertainty in Hi.
1400! Uho - Uncertainty in Ho.
1410! Ukm - Uncertainty in tube thermal conductivity.
1420! Ukw - Uncertainty in coolant thermal conductivity.
1430! Ulmtd - Uncertainty in LMTD.
1440! Um - Uncertainty in M.
1450! Umd - Uncertainty in coolant mass flow.
1460! Umu - Uncertainty in coolant viscosity.
1470! Untercept - Uncertainty in Ntercept.
1480! Uo - Overall heat transfer coefficient (K/W).
1490! Uomega - Uncertainty in Omega.
```

```
1500! Uppk1 - Uncertainty in Ppk1.
1510! Uppk2 - Uncertainty in Ppk2.
1520! Upp1 - Uncertainty in Pp1.
1530! Upp2 - Uncertainty in Pp2.
1540! Upr - Uncertainty in coolant Prandtl number.
1550! Uqp - Uncertainty in Qp.
1560! Uqtz - Uncertainty in quartz thermometer readings.
1570! Ure - Uncertainty in Reynolds number.
1580! Urho - Uncertainty in coolant density.
1590! Urhot1 - Uncertainty in coolant density as a function of inlet temp.
1600! Uslope - Uncertainty in Slope.
1610! Utavg - Uncertainty in average coolant temperature.
1620! Utcor - Uncertainty in Tcor.
1630! Utcpl - Uncertainty in steam thermocouple measurements.
1640! Utfilm - Uncertainty in Tfilm.
1650! Utrise - Uncertainty in Trise.
1660! Utwo - Uncertainty in Two.
1670! Utxf - Uncertainty in Txf.
1680! Uuo - Uncertainty in Uo.
1690! Uvcw - Uncertainty in coolant water velocity.
1700! Uxi - Uncertainty in Xi.
1710! Vcw - Cooling water average velocity (m/s).
1720! Vf - Cooling water volumetric flow (m^3/s).
1730! X - Independent variable in function Y=f(X).  Used for curve fitting by
1740!       least squares method.
1750! Xbar - Arithmetic mean of X.
1760! Xi - Greek "Xi" in Petukhov's equation Nu=f(Re,Pr).
1770! Y - Dependent variable in function Y=f(X).  Used for curve fitting by
1780!       least squares method.
1790! Ybar - Arithmetic mean of Y.
1800!
1810!
1820!
1830  COM /Hfg/ C1(5)
1840  COM /Muw/ C2(8)
1850  COM /Rhow/ C3(6)
1860  COM /Kw/ C4(5)
1870  COM /Cpw/ C5(5)
1880  COM /Urho/ C6(5)
1890  COM /Ucp/ C7(4)
1900  COM /Uk/ C8(4)
1910  COM /Umu/ C9(7)
1920  COM /Upr/ C10(4)
1930  COM /Uhfg/ C11(4)
1940  DIM Array(27,8)
1950!
1960! Read function constants.
1970  DATA -0.96917486E-9,0.23213696E-6,-0.30487402E-4
```

```
1980  DATA 0.10148364E-2,-0.23700473E1,0.25005197E4
1990  READ C1(*)
2000  DATA 0.1078869E-11,-0.50954132E-9,0.10329146E-6,-0.11878223E-4
2010  DATA 0.8736755E-3,-0.4512923E-1,0.18275094E1,-0.63745948E2,0.180019E4
2020  READ C2(*)
2030  DATA -0.86244597E-11,0.39067797E-8,-0.76318631E-6,0.88129446E-4
2040  DATA -0.90737942E-2,0.70640988E-1,0.9998103E3
2050  READ C3(*)
2060  DATA -0.51282051E-8,0.18735431E-5,-0.23712121E-3
2070  DATA 0.30282634E-2,0.18883438E1,0.56103333E3
2080  READ C4(*)
2090  DATA -4.8411511E-8,1.529196E-5,-1.8467308E-3,.1145064,-3.431451,4216.853
2100  READ C5(*)
2110  DATA -5.17467582E-11,1.95338886E-8,-3.06274524E-6,2.64388338E-4
2120  DATA -1.81475884E-2,0.70540968E-1
2130  READ C6(*)
2140  DATA -24.2057555E-8,6.116784E-5,-5.5401627E-3,.2290128,-3.431451
2150  READ C7(*)
2160  DATA -2.56410255E-8,0.74941724E-5,-0.71136363E-3
2170  DATA 0.60565268E-2,0.18883438E1
2180  READ C8(*)
2190  DATA 0.8630952E-11,-3.56678924E-9,0.61874876E-6,-0.59391115E-4
2200  DATA 3.494702E-3,-1.3538769E-1,0.36550188E1,-0.63745948E2
2210  READ C9(*)
2220  DATA -1.1866107E-7,9.95561E-6,-5.2464478E-4,2.1177156E-2,-.4616896
2230  READ C10(*)
2240  DATA -4.8458743E-6,9.2854784E-4,-9.1462206E-2,2.0296728,-2370.0473
2250  READ C11(*)
2260  !
2270  BEEP
2280  INPUT "GIVE THE NAME OF THE EXISTING DATA FILE",D_file$
2290  ASSIGN @File TO D_file$
2300  PRINTER IS 701
2310  Nrun=14
2320  BEEP
2330  INPUT "ENTER THE NUMBER OF DATA POINTS (Default=14)",Nrun
2340  ENTER @File;Ifg,Imc,Ipc
2350  ENTER @File;Ddd,Ddd,Ddd
2360  ENTER @File;Di,Droot
2370  !
2380  ! Initialize tube geometry and thermal conductivity.
2390  L=.13335
2400  L1=.060325
2410  L2=.034925
2420  Areacorr=9.18214E-6
2430  IF Imc=0 THEN Km=390.8
2440  IF Imc=1 THEN Km=14.3
2450  IF Imc=2 THEN Km=231.8
```

```
2460  IF Imc=3 THEN Km=55.3
2470  Ci=2.5
2480  Alp=2.6
2490  !
2500  IF Ipc=0 THEN
2510     Alpsm=.815
2520     Ualpsm=.0141
2530     Utstm=.2
2540  ELSE
2550     Alpsm=.827
2560     Ualpsm=.0076
2570     Utstm=.4
2580  END IF
2590  Uqtz=.05
2600  Ukm=1.0
2610  Ufm=.5
2620  !
2630  Rm=LOG(Droot/Di)/(2.0*PI*L*Km)
2640  P=PI*Di
2650  A=(Droot^2-Di^2)*PI/4.0
2660  PRINT USING "1X,""Uncertainty analysis done on file:          "",10A";D_fi
le$
2670  PRINT
2680  PRINT USING "1X,""Uncertainty in coolant temperatures:        "",Z.3D,"" (
degC)""";Uqtz
2690  PRINT USING "1X,""Uncertainty in steam temperature:           "",Z.3D,"" (
degC)""";Utstm
2700  PRINT USING "1X,""Uncertainty in tube thermal conductivity:   "",Z.3D,"" (
W/m-K)""";Ukm
2710  PRINT USING "1X,""Uncertainty in flowmeter reading:           "",Z.3D,"" (
pct flow)""";Ufm
2720  PRINT
2730  !
2740  ! Read file and compute necessary values for Wilson iteration.  Store
2750  ! these values in Array for iterative processing.
2760  FOR J=0 TO Nrun-1
2770  !
2780  ! Calculate the properties of the cooling water at its avg temperature.
2790  ! Based on these properties, calculate Omega by Petukhov theory.
2800  ! Calculate the uncertainties of the fluid properties and the variables.
2810     ENTER @File;Fm,T1,T2,Tsteam,Ddd,Ddd,Ddd,Ddd,Ddd
2820     Md=(.6763*Fm+1.34212)*FNRhow(T1)/1.E+6
2830     Urhot1=FNUrho(T1,Uqtz)
2840     P1=Urhot1*(Fm+1.9845)
2850     P2=Ufm*FNRhow(T1)
2860     Umd=6.763E-6*(P1^2+P2^2)^.5
2870     !
2880     Tavg=(T1+T2)/2.0
```

```
2890      Utavg=Uqtz*(2.0)^.5/2.0
2900      !
2910      Cpcw=FNCpw(Tavg)
2920      Ucp=FNUcp(Tavg,Utavg)
2930      !
2940      Rhocw=FNRhow(Tavg)
2950      Urho=FNUrho(Tavg,Utavg)
2960      !
2970      Kcw=FNKw(Tavg)
2980      Ukw=FNUk(Tavg,Utavg)
2990      !
3000      Mucw=FNMuw(Tavg)
3010      Umu=FNUmu(Tavg,Utavg)
3020      !
3030      Prcw=FNPrw(Tavg)
3040      Upr=FNUpr(Tavg,Utavg)
3050      !
3060      Vf=Md/Rhocw
3070      Vcw=4.0*Vf/(PI*Di^2-Areacorr)
3080      P3=Umd/Md
3090      P4=Urho/Rhocw
3100      Uvcw=Vcw*(P3^2+P4^2)^.5
3110      !
3120      Rei=Rhocw*Vcw*Di/Mucw
3130      P5=Uvcw/Vcw
3140      P6=Umu/Mucw
3150      Ure=Rei*(P4^2+P5^2+P6^2)^.5
3160      !
3170      Xi=(1.82*LGT(Rei)-1.64)^(-2)
3180      Uxi=1.58*Xi^1.5*Ure/Rei
3190      !
3200      Ppk1=1.0+3.4*Xi
3210      Uppk1=3.4*Uxi
3220      !
3230      Ppk2=11.7+1.8*Prcw^(-1.0/3.0)
3240      Uppk2=.6*Prcw^(-4./3.)*Upr
3250      !
3260      Pp1=(Xi/8.0)*Rei*Prcw
3270      P7=Uxi/Xi
3280      P8=Upr/Prcw
3290      P9=Ure/Rei
3300      Upp1=Pp1*(P7^2+P8^2+P9^2)^.5
3310      !
3320      Pp2=Ppk1+Ppk2*(Xi/8.0)^.5*(Prcw^.6667-1.0)
3330      P10=Uppk1/(Pp2-Ppk1)
3340      P11=Uppk2/Ppk2
3350      P12=(2.*Prcw^(-.3333)*Upr)/(3.*(Prcw^(.6667)-1.))
3360      Upp2=(Pp2-Ppk1)*(P10^2+P11^2+P12^2+(P7/2.)^2)^.5
```

```
3370      !
3380      Omega=Pp1/Pp2
3390      P13=Upp1/Pp1
3400      P14=Upp2/Pp2
3410      Uomega=Omega*(P13^2+P14^2)^,5
3420      !
3430   !
3440   ! Calculate the log-mean-temp-difference after correcting for the
3450   ! frictional effects of heating.  Then calculate the heat flux and
3460   ! overall heat transfer coefficient and their uncertainties.
3470      Tcor=FNTfric(Vcw)
3480      Utcor=(2.*2.4669874E-3*Vcw-6.6467669E-4)*Uvcw
3490      !
3500      Trise=T2-T1-Tcor
3510      Utrise=(2.0*Uqtz^2+Utcor^2)^.5
3520      !
3530      Lmtd=Trise/LOG((Tsteam-T1)/(Tsteam-T2+Tcor))
3540      P15=Utrise/Lmtd
3550      P16=(T1-T2+Tcor)*Utstm/((Tsteam-T1)*(Tsteam-T2+Tcor))
3560      P17=Uqtz/(Tsteam-T1)
3570      P18=Uqtz/(Tsteam-T2+Tcor)
3580      P19=Utcor/(Tsteam-T2+Tcor)
3590      Ulmtd=Lmtd^2/Trise*(P15^2+P16^2+P17^2+P18^2+P19^2)^.5
3600      !
3610      Q=Md*Cpcw*Trise
3620      Qp=Q/(PI*Droot*L)
3630      P20=Utrise/Trise
3640      P21=Ucp/Cpcw
3650      Uqp=Qp*(P20^2+P3^2+P21^2)^.5
3660      !
3670      Uo=Qp/Lmtd
3680      P22=Uqp/Qp
3690      P23=Ulmtd/Lmtd
3700      Uuo=Uo*(P22^2+P23^2)^.5
3710      !
3720   !
3730   ! Store the necessary values for Wilson iteration.
3740      Array(J,0)=Tsteam
3750      Array(J,1)=Kcw
3760      Array(J,2)=Qp
3770      Array(J,3)=Uo
3780      Array(J,4)=Omega
3790      Array(J,5)=Uomega
3800      Array(J,6)=Ukw
3810      Array(J,7)=Uuo
3820      Array(J,8)=Uqp
3830   NEXT J
3840   ASSIGN @File TO *
```

```
3850 !
3860 ! Iterate for Ci and Alp until they converge within 0.05% of Cic and Alpc.
3870 BEEP
3880 Sumx=0.
3890 Sumy=0.
3900 Sumx2=0.
3910 Sumy2=0.
3920 Sumxy=0.
3930 FOR J=0 TO Nrun-1
3940    Tsteam=Array(J,0)
3950    Kcw=Array(J,1)
3960    Qp=Array(J,2)
3970    Uo=Array(J,3)
3980    Omega=Array(J,4)
3990 !
4000 ! Solve for Two by iteration and than find Hi.
4010    Two=Tsteam-5.0
4020    Tfilm=(Tsteam+2.0*Two)/3.0
4030    Rhof=FNRhow(Tfilm)
4040    Kf=FNKw(Tfilm)
4050    Muf=FNMuw(Tfilm)
4060    Hfgf=FNHfg(Tfilm)+.68*FNCpw(Tfilm)*(Tsteam-Two)
4070    New=(Kf^3*9.81*Hfgf*Rhof^2/(Muf*Droot*(Tsteam-Two)))^.25
4080    Ho=Alp*New
4090    Twoc=Tsteam-Qp/Ho
4100    IF ABS((Twoc-Two)/Twoc)>.001 THEN
4110       Two=Twoc
4120       GOTO 4020
4130    END IF
4140    Hi=Kcw/Di*Ci*Omega
4150    M=(Hi*P/(Km*A))^.5
4160    Fe1=FNTanh(M*L1)/(M*L1)
4170    Fe2=FNTanh(M*L2)/(M*L2)
4180 !
4190 ! Compute the Wilson data points for linear regression.
4200    X=Droot*New*L/(Omega*Kcw*(L+L1*Fe1+L2*Fe2))
4210    Y=New*(1.0/Uo-Rm*PI*Droot*L)
4220    Sumx=Sumx+X
4230    Sumy=Sumy+Y
4240    Sumx2=Sumx2+X*X
4250    Sumy2=Sumy2+Y*Y
4260    Sumxy=Sumxy+X*Y
4270 NEXT J
4280 !
4290 ! Compute the slope and intercept of the Modified Wilson plot.  Take the
4300 ! reciprocals to compute Alpc and Cic.  Compare with the last values of
4310 ! Alp and Ci.  If out of tolerance, average their values and repeat entire
4320 ! analysis with the revised values.
```

```
4330  Sxx=Sumx2-Sumx^2/Nrun
4340  Sxy=Sumxy-Sumx*Sumy/Nrun
4350  Xbar=Sumx/Nrun
4360  Ybar=Sumy/Nrun
4370  Slope=Sxy/Sxx
4380  Ntercept=Ybar-Slope*Xbar
4390  Cic=1.0/Slope
4400  Alpc=1.0/Ntercept
4410  Cerr=ABS((Cic-Ci)/Cic)
4420  Aerr=ABS((Alpc-Alp)/Alpc)
4430  Ci=(Ci+Cic)/2.0
4440  Alp=(Alp+Alpc)/2.0
4450  IF Cerr>.0005 OR Aerr>.0005 THEN GOTO 3870
4460  !
4470  ! Once final values of Ci and Alp are found, compute the regression
4480  ! coefficient of the Modified Wilson plot.  Find the enhancements for
4490  ! constant heat flux and constant temperature drop across the film.
4500  ! Determine the uncertainty bands about Alp, Ci, and the enhancements
4510  ! based on a 95% confidence interval and Nrun-2 degrees of freedom.
4520  ! Print results.
4530  Syy=Sumy2-Nrun*Ybar^2
4540  Sse=Syy-Slope*Sxy
4550  Sigmahat2=Sse/(Nrun-2.0)
4560  Tau=2.179  ! For a 95% confidence interval with 12 deg freedom.
4570  IF Nrun=28 THEN Tau=2.056
4580  Uslope=Tau*(Sigmahat2/Sxx)^.5
4590  Uci=Uslope/(Slope*Slope)
4600  Untercpt=Tau*(Sigmahat2*(1.0/Nrun+Xbar^2/Sxx))^.5
4610  Ualp=Untercpt/(Ntercept*Ntercept)
4620  PRINT USING "1X,""Uncertainty in Ci:"",25X,DD.2D,""  (pct)""";Uci*100./Ci
4630  PRINT USING "1X,""Uncertainty in Alp:"",24X,DD.2D,""  (pct)""";Ualp*100./A
lp
4640  IF Ifg=1 THEN
4650     Et=Alp/Alpsm
4660     Uet=Et*((Ualp/Alp)^2+(Ualpsm/Alpsm)^2)^.5
4670     Eq=Et^(4.0/3.0)
4680     Ueq=1.333*Uet*Et^(1./3.)
4690  PRINT USING "1X,""Uncertainty in Enhancement (const flux):"",3X,DD.2D,""
(pct)""";Ueq*100./Eq
4700  PRINT USING "1X,""Uncertainty in Enhancement (const DelT):"",3X,DD.2D,""
(pct)""";Uet*100./Et
4710  END IF
4720  PRINT
4730  PRINT USING "8X,""Uncertainty  Uncertainty  Uncertainty  Uncertainty  Unce
rtainty"""
4740  PRINT USING "10X,""Overall      Outside       Inside         Heat           F
ilm"""
4750  PRINT USING "11X,""H.T.C.       H.T.C.       H.T.C.         Flux           Del
```

```
taT"""
4760  PRINT USING "11X,""(pct)        (pct)        (pct)        (pct)        (pc
t)"""
4770  PRINT
4780  !
4790  ! Calculate and print the percent uncertainties in Uc, Hi, Ho, Qp, and
4800  ! Txf.
4810  Hoavg=0.
4820  Uhoavg=0.
4830  FOR J=0 TO Nrun-1
4840     Tsteam=Array(J,0)
4850     Kcw=Array(J,1)
4860     Qp=Array(J,2)
4870     Uo=Array(J,3)
4880     Omega=Array(J,4)
4890     Uomega=Array(J,5)
4900     Ukw=Array(J,6)
4910     Uuo=Array(J,7)
4920     Uqp=Array(J,8)
4930     !
4940     Hi=Kcw/Di*Ci*Omega
4950     P24=Uomega/Omega
4960     P25=Uci/Ci
4970     P26=Ukw/Kcw
4980     Uhi=Hi*(P24^2+P25^2+P26^2)^.5
4990     !
5000     Utwo=Utstm
5010     Txf=Tsteam-Two
5020     Utxf=(Utstm^2+Utwo^2)^.5
5030     Tfilm=(Tsteam+2.0*Two)/3.0
5040     Utfilm=(Utstm^2+4.0*Utwo^2)/3.0
5050     Rhof=FNRhow(Tfilm)
5060     Kf=FNKw(Tfilm)
5070     Muf=FNMuw(Tfilm)
5080     Hfgf=FNHfg(Tfilm)+.68*FNCpw(Tfilm)*Txf
5090     New=(Kf^3*9.81*Hfgf*Rhof^2/(Muf*Droot*Txf))^.25
5100     P39=3.0*FNUk(Tfilm,Utfilm)/Kf
5110     P40=((FNUhfg(Tfilm,Utfilm))^2+(.68*Txf*FNUcp(Tfilm,Utfilm))^2+(.68*FNCp
w(Tfilm)*Utxf)^2)^.5
5120     P40=P40/Hfgf
5130     P41=2.0*FNUrho(Tfilm,Utfilm)/Rhof
5140     P42=FNUmu(Tfilm,Utfilm)/Muf
5150     P43=Utxf/Txf
5160     Unew=.25*New*(P39^2+P40^2+P41^2+P42^2+P43^2)^.5
5170     Ho=Alp*New
5180     Uho=((Alp*Unew)^2+(New*Ualp)^2)^.5
5190     Twoc=Tsteam-Qp/Ho
5200     Utwoc=(Utstm^2+(Uqp/Ho)^2+(Qp*Uho/(Ho*Ho))^2)^.5
```

```
5210     IF ABS((Twoc-Two)/Twoc)>.001 THEN
5220        Two=Twoc
5230        Utwo=Utwoc
5240        GOTO 5010
5250     END IF
5260   !
5270     PRINT USING "1X,DD,5(8X,DD.DD)";J+1,Uuo*100/Uo,Uho*100/Ho,Uhi*100/Hi,Uqp
*100/Qp,Utxf*100/Txf
5280   NEXT J
5290   END
5300   !
5310   !
5320   !
5330   !
5340   DEF FNHfg(T)
5350   ! This function takes saturation temp [degC] of water and returns latent
5360   ! heat of vaporization [J/kg].
5370   !
5380   COM /Hfg/ C1(5)
5390   Hfg=C1(0)
5400   FOR I=1 TO 5
5410      Hfg=Hfg*T+C1(I)
5420   NEXT I
5430   Hfg=Hfg*1.E+3
5440   RETURN Hfg
5450   FNEND
5460   !
5470   !
5480   !
5490   DEF FNMuw(T)
5500   ! This function takes saturation temperature of water [degC] and returns
5510   ! viscosity [kg/m-s].
5520   !
5530   COM /Muw/ C2(8)
5540   Mu=C2(0)
5550   FOR I=1 TO 8
5560      Mu=Mu*T+C2(I)
5570   NEXT I
5580   Mu=Mu*1.E-6
5590   RETURN Mu
5600   FNEND
5610   !
5620   !
5630   !
5640   DEF FNCpw(T)
5650   ! This function takes saturation temp of water [degC] and returns
5660   ! specific heat [J/kg-K].
5670   !
```

```
5680  COM /Cpw/ C5(5)
5690  Cp=C5(0)
5700  FOR I=1 TO 5
5710     Cp=Cp*T+C5(I)
5720  NEXT I
5730  RETURN Cp
5740  FNEND
5750  !
5760  !
5770  !
5780  DEF FNRhow(T)
5790  ! This function takes water temp [degC] and returns density [kg/m^3].
5800  !
5810  COM /Rhow/ C3(5)
5820  Ro=C3(0)
5830  FOR I=1 TO 5
5840     Ro=Ro*T+C3(I)
5850  NEXT I
5860  RETURN Ro
5870  FNEND
5880  !
5890  !
5900  !
5910  DEF FNPrw(T)
5920  ! This function takes water temp [degC] and returns Prandtl Number.
5930  !
5940  Prw=FNCpw(T)*FNMuw(T)/FNKw(T)
5950  RETURN Prw
5960  FNEND
5970  !
5980  !
5990  !
6000  DEF FNKw(T)
6010  ! This function takes water temp [degC] and returns thermal conductivity
6020  ! coefficient [W/m-K].
6030  !
6040  COM /Kw/ C4(5)
6050  Kw=C4(0)
6060  FOR I=1 TO 5
6070     Kw=Kw*T+C4(I)
6080  NEXT I
6090  Kw=Kw*1.E-3
6100  RETURN Kw
6110  FNEND
6120  !
6130  !
6140  !
6150  DEF FNTanh(X)
```

```
6160  ! This function computes the hyperbolic tangent of a number.
6170  !
6180  P=EXP(X)
6190  Q=EXP(-X)
6200  Tanh=(P-Q)/(P+Q)
6210  RETURN Tanh
6220  FNEND
6230  !
6240  !
6250  !
6260  DEF FNTfric(Vcw)
6270  ! This function takes coolant velocity [m/s] and returns the increase in
6280  ! water temp [degC] due solely to frictional heating of the internal
6290  ! flow.  This increase was determined by curve fitting the temp rise
6300  ! obtained by circulating coolant at velocities ranging from 1.1 to 4.9
6310  ! m/s through tubes of I.D. 12.14 to 13.37 mm with HEATEX insert.
6320  !
6330  Tcor=2.4669874E-3*Vcw^2-6.6467689E-4*Vcw-5.010371E-4
6340  RETURN Tcor
6350  FNEND
6360  !
6370  !
6380  !
6390  DEF FNUmu(T,Ut)
6400  ! This function calculates the uncertainty in viscosity as a function of
6410  ! the uncertainty in temperature and a precision error of 0.1.
6420  !
6430  COM /Umu/ C9(7)
6440  Umu=C9(0)
6450  FOR I=1 TO 7
6460      Umu=Umu*T+C9(I)
6470  NEXT I
6480  Umu=(Umu*Ut+.1)/1.E+6
6490  RETURN Umu
6500  FNEND
6510  !
6520  !
6530  !
6540  DEF FNUrho(T,Ut)
6550  ! This function calculates the uncertainty in density as a function of the
6560  ! uncertainty in temperature and a 0.01 kg/m^3 precision error.
6570  !
6580  COM /Urho/ C6(5)
6590  Urho=C6(0)
6600  FOR I=1 TO 5
6610      Urho=Urho*T+C6(I)
6620  NEXT I
6630  Urho=Urho*Ut+.01
```

```
6640  RETURN Urho
6650  FNEND
6660  !
6670  !
6680  !
6690  DEF FNUcp(T,Ut)
6700  ! This function calculates the uncertainty in specific heat as a function
6710  ! of the uncertainty in temperature and a 1.0 J/kg-K precision error.
6720  !
6730  COM /Ucp/ C7(4)
6740  Ucp=C7(0)
6750  FOR I=1 TO 4
6760     Ucp=Ucp*T+C7(I)
6770  NEXT I
6780  Ucp=Ucp*Ut+1.0
6790  RETURN Ucp
6800  FNEND
6810  !
6820  !
6830  !
6840  DEF FNUk(T,Ut)
6850  ! This function calculates the uncertainty in water thermal conductivity
6860  ! as a function of temperature and a 0.1E-3 precision error.
6870  !
6880  COM /Uk/ C8(4)
6890  Uk=C8(0)
6900  FOR I=1 TO 4
6910     Uk=Uk*T+C8(I)
6920  NEXT I
6930  Uk=(Uk*Ut+.1)/1.E+3
6940  RETURN Uk
6950  FNEND
6960  !
6970  !
6980  !
6990  DEF FNUpr(T,Ut)
7000  ! This function calculates the uncertainty in Prandtl number as a function
7010  ! of temperature and a 0.01 precision error.
7020  !
7030  COM /Upr/ C10(4)
7040  Upr=C10(0)
7050  FOR I=1 TO 4
7060     Upr=Upr*T+C10(I)
7070  NEXT I
7080  Upr=Upr*Ut+.01
7090  RETURN Upr
7100  FNEND
7110  !
```

```
7120  !
7130  !
7140  DEF FNUhfg(T,Ut)
7150  ! This function calculates the uncertainty in latent heat of vaporization
7160  ! as a function of the uncertainty in temperature and a 1 kJ/kg precision
7170  ! error.
7180  !
7190  COM /Uhfg/ C11(4)
7200  Uhfg=C11(0)
7210  FOR I=1 TO 4
7220     Uhfg=Uhfg*T+C11(I)
7230  NEXT I
7240  Uhfg=Uhfg*Ut+1000.
7250  RETURN Uhfg
7260  FNEND
```

```
Uncertainty analysis done on file:             SSMTV3

Uncertainty in coolant temperatures:           0.050 (degC)
Uncertainty in steam temperature:              0.200 (degC)
Uncertainty in tube thermal conductivity:      1.000 (W/m-K)
Uncertainty in flowmeter reading:              0.500 (pct flow)

Uncertainty in Ci:                             4.02  (pct)
Uncertainty in Alp:                            2.07  (pct)

        Uncertainty  Uncertainty  Uncertainty  Uncertainty  Uncertainty
          Overall      Outside      Inside        Heat         Film
          H.T.C.       H.T.C.       H.T.C.        Flux        DeltaT
          (pct)        (pct)        (pct)        (pct)        (pct)

 1        23.11        2.11         4.07         13.34         1.48
 2        20.26        5.17         4.09         11.71        11.99
 3        18.21        4.69         4.11         10.53        11.61
 4        15.55        3.85         4.14          9.00         9.91
 5        13.22        3.25         4.21          7.69         8.52
 6        10.65        2.85         4.34          6.27         7.12
 7         8.31        2.61         4.67          5.13         6.14
 8         8.29        2.14         4.67          5.12         2.13
 9        10.66        2.84         4.34          6.27         7.13
10        13.09        3.24         4.21          7.61         8.44
11        15.52        3.84         4.14          8.98         9.89
12        17.94        4.68         4.11         10.37        11.45
13        20.88        5.13         4.09         12.06        12.34
14        23.01        7.26         4.07         13.29        15.07
```

```
Uncertainty analysis done on file:          SSMTV4

Uncertainty in coolant temperatures:        0.050 (degC)
Uncertainty in steam temperature:           0.200 (dagC)
Uncertainty in tube thermal conductivity:   1.000 (W/m-K)
Uncertainty in flowmeter reading:           0.500 (pct flow)

Uncertainty in Ci:                          4.86  (pct)
Uncertainty in Alp:                         2.45  (pct)

           Uncertainty  Uncertainty  Uncertainty  Uncertainty  Uncertainty
             Overall      Outside       Inside        Heat         Film
              H.T.C.       H.T.C.       H.T.C.        Flux        DeltaT
              (pct)        (pct)        (pct)         (pct)        (pct)

  1           23.12         7,49         5,00         13.35        14.93
  2           21.24         6.14         5.01         12.27        13.77
  3           18.36         2.48         5.03         10.61         1.55
  4           15.90         4.16         5.06          9.20        10.23
  5           13.31         3.57         5.11          7.74         8.68
  6           10.79         3.17         5,22          6.34         7.33
  7            8.34         2.95         5.49          5.15         6.29
  8            8.35         2.92         5,49          5.15         6.10
  9           10.79         3.17         5.22          6.34         7.33
 10           13.08         3.56         5.11          7.60         8.56
 11           15.67         4.16         5,06          9.07        10.09
 12           18.24         5.02         5,03         10.54        11.74
 13           20.90         6.01         5.01         12.08        13.33
 14           23.36         7.74         6,00         13.49        15.45
```

```
Uncertainty analysis done on file:          S16V1

Uncertainty in coolant temperatures:        0.050 (degC)
Uncertainty in steam temperature:           0.200 (degC)
Uncertainty in tube thermal conductivity:   1.000 (W/m-K)
Uncertainty in flowmeter reading:           0.500 (pct flow)

Uncertainty in Ci:                          3.52  (pct)
Uncertainty in Alp:                         2.69  (pct)
Uncertainty in Enhancement (const flux):    4.26  (pct)
Uncertainty in Enhancement (const DelT):    3.20  (pct)

      Uncertainty  Uncertainty  Uncertainty  Uncertainty  Uncertainty
        Overall      Outside       Inside       Heat         Film
        H.T.C.       H.T.C.        H.T.C.       Flux        DeltaT
        (pct)        (pct)         (pct)        (pct)        (pct)

 1      19.98         4.89          3.58        11.54        12.58
 2      17.57         4.37          3.60        10.15        11.15
 3      15.55         3.96          3.62         8.99        10.01
 4      13.49         3.64          3.66         7.82         8.84
 5      11.62         3.40          3.73         6.77         7.88
 6       9.56         3.23          3.88         5.65         6.92
 7       7.54         3.12          4.24         4.72         6.29
 8       7.54         2.77          4.24         4.72         2.74
 9       9.45         3.22          3.88         5.60         6.87
10      11,39         3.38          3.73         6.64         7.74
11      13.48         3.63          3.66         7.81         8.84
12      15.36         3.95          3.62         8.88         9.89
13      17.76         4.22          3.60        10.25        10.78
14      19.62         4.91          3.58        11.33        12.46
```

```
Uncertainty analysis done on file:             S16V2

Uncertainty in coolant temperatures:           0.050 (degC)
Uncertainty in steam temperature:              0.200 (degC)
Uncertainty in tube thermal conductivity:      1.000 (W/m-K)
Uncertainty in flowmeter reading:              0.500 (pct flow)

Uncertainty in Ci:                             3.39  (pct)
Uncertainty in Alp:                            2.61  (pct)
Uncertainty in Enhancement (const flux):       4.17  (pct)
Uncertainty in Enhancement (const DelT):       3.13  (pct)

      Uncertainty  Uncertainty  Uncertainty  Uncertainty  Uncertainty
        Overall      Outside      Inside        Heat          Film
        H.T.C.       H.T.C.       H.T.C.        Flux         DeltaT
        (pct)        (pct)        (pct)         (pct)         (pct)

 1      19.78         2.66         3.45         11.42          1.80
 2      17.84         4.32         3.46         10.31         11.28
 3      15.71         3.91         3.49          9.09         10.08
 4      13.52         3.57         3.53          7.93          8.81
 5      11.69         3.34         3.61          6.81          7.89
 6       9.52         3.15         3.76          5.63          6.67
 7       7.55         3.05         4.13          4.72          6.26
 8       7.57         2.70         4.13          4.73          2.78
 9       9.55         3.15         3.76          5.65          6.89
10      11.50         3.32         3.61          6.70          7.78
11      13.49         3.57         3.53          7.82          8.82
12      15.44         3.89         3.49          8.93          9.92
13      17.68         4.30         3.46         10.22         11.18
14      19.69         4.81         3.45         11.38         12.39
```

```
Uncertainty analysis done on file:          S28V1

Uncertainty in coolant temperatures:        0.050 (degC)
Uncertainty in steam temperature:           0.200 (degC)
Uncertainty in tube thermal conductivity:   1.000 (W/m-K)
Uncertainty in flowmeter reading:           0.500 (pct flow)

Uncertainty in Ci:                          2.48  (pct)
Uncertainty in Alp:                         2.10  (pct)
Uncertainty in Enhancement (const flux):    3.63  (pct)
Uncertainty in Enhancement (const DelT):    2.72  (pct)

        Uncertainty  Uncertainty  Uncertainty  Uncertainty  Uncertainty
          Overall      Outside      Inside        Heat         Film
          H.T.C.       H.T.C.       H.T.C.        Flux        DeltaT
          (pct)        (pct)        (pct)        (pct)        (pct)

  1       18.89         4.19         2.56        10.91        11.77
  2       16.99         3.76         2.59         9.82        10.65
  3       15.43         3.43         2.62         8.93         9.78
  4       13.31         3.12         2.88         7.71         8.59
  5       11.28         2.87         2.77         6.57         7.53
  6        9.35         2.70         2.97         5.53         6.67
  7        7.50         2.61         3.43         4.89         6.15
  8        7.50         2.23         3.43         4.69         3.02
  9        9.33         2.70         2.97         5.52         6.66
 10       11.22         2.87         2.77         6.54         7.50
 11       13.24         3.11         2.68         7.68         8.55
 12       15.28         3.42         2.62         8.84         9.69
 13       17.32         3.78         2.59        10.01        10.83
 14       19.42         4.22         2.56        11.21        12.08
```

```
Uncertainty analysis done on file:            S28V2

Uncertainty in coolant temperatures:          0.050 (degC)
Uncertainty in steam temperature:             0.200 (degC)
Uncertainty in tube thermal conductivity:     1.000 (W/m-K)
Uncertainty in flowmeter reading:             0.500 (pct flow)

Uncertainty in Ci:                            3.05  (pct)
Uncertainty in Alp:                           2.68  (pct)
Uncertainty in Enhancement (const flux):      4.26  (pct)
Uncertainty in Enhancement (const DelT):      3.19  (pct)

        Uncertainty  Uncertainty  Uncertainty  Uncertainty  Uncertainty
          Overall      Outside      Inside        Heat         Film
          H.T.C.       H.T.C.       H.T.C.        Flux        DeltaT
          (pct)        (pct)        (pct)        (pct)        (pct)

 1        19.20        4.62         3.11         11.09        12.15
 2        17.40        4.21         3.13         10.05        11.07
 3        15.38        3.85         3.16          8.90         9.88
 4        13.37        3.58         3.21          7.75         8.80
 5        11.43        3.37         3.28          6.66         7.81
 6         9.45        3.22         3.45          5.59         6.94
 7         7.62        3.14         3.85          4.76         6.47
 8         7.59        2.79         3.86          4.75         3.04
 9         9.55        3.23         3.45          5.65         7.01
10        11.58        3.38         3.29          6.75         7.91
11        13.60        3.60         3.21          7.88         8.93
12        15.48        3.86         3.18          8.95         9.96
13        17.39        4.20         3.13         10.05        11.06
14        19.78        4.46         3.11         11.42        11.91
```

```
Uncertainty analysis done on file:          S28V3

Uncertainty in coolant temperatures:        0.050 (degC)
Uncertainty in steam temperature:           0.200 (degC)
Uncertainty in tube thermal conductivity:   1.000 (W/m-K)
Uncertainty in flowmeter reading:           0.500 (pct flow)

Uncertainty in Ci:                          3.35  (pct)
Uncertainty in Alp:                         2.80  (pct)
Uncertainty in Enhancement (const flux):    4.39  (pct)
Uncertainty in Enhancement (const DelT):    3.29  (pct)

          Uncertainty  Uncertainty  Uncertainty  Uncertainty  Uncertainty
            Overall      Outside      Inside         Heat         Film
            H.T.C.       H.T.C.       H.T.C.         Flux        DeltaT
            (pct)        (pct)        (pct)          (pct)        (pct)

  1         19.26         4.77         3.41         11.13        12.17
  2         17.47         4.35         3.42         10.10        11.15
  3         15.39         3.97         3.45          8.90         9.91
  4         13.51         3.70         3.49          7.83         8.91
  5         11.54         3.48         3.57          6.72         7.90
  6          9.41         3.32         3.72          5.57         6.93
  7          7.53         3.23         4.10          4.71         6.41
  8          7.53         2.89         4.10          4.71         2.92
  9          9.49         3.32         3.72          5.61         6.99
 10         11.40         3.47         3.57          6.64         7.82
 11         13.34         3.69         3.49          7.73         8.81
 12         15.42         3.88         3.45          8.92         9.96
 13         17.40         4.34         3.42         10.05        11.11
 14         19.37         4.76         3.41         11.19        12.23
```

```
Uncertainty analysis done on file:           S38V2

Uncertainty in coolant temperatures:         0.050 (degC)
Uncertainty in steam temperature:            0.200 (degC)
Uncertainty in tube thermal conductivity:    1.000 (W/m-K)
Uncertainty in flowmeter reading:            0.500 (pct flow)

Uncertainty in Ci:                           2.69  (pct)
Uncertainty in Alp:                          1.87  (pct)
Uncertainty in Enhancement (const flux):     3.40  (pct)
Uncertainty in Enhancement (const DelT):     2.55  (pct)

        Uncertainty  Uncertainty  Uncertainty  Uncertainty  Uncertainty
          Overall      Outside      Inside        Heat         Film
           H.T.C.       H.T.C.       H.T.C.       Flux        DeltaT
           (pct)        (pct)        (pct)        (pct)        (pct)

  1        22.20         4.70         2.76        12.82        13.09
  2        20.00         4.32         2.78        11.55        12.41
  3        17.50         3.73         2.81        10.12        10.91
  4        15.22         3.27         2.87         8.81         9.61
  5        12.91         2.90         2.96         7.51         8.33
  6        10.62         2.63         3.14         6.25         7.19
  7         8.26         2.45         3.58         5.10         6.28
  8         8.26         1.99         3.58         5.10         2.72
  9        10.54         2.63         3.14         6.21         7.14
 10        12.90         2.90         2.96         7.50         8.32
 11        15.29         3.28         2.87         8.85         9.65
 12        17.56         3.74         2.81        10.15        10.98
 13        19.91         4.30         2.78        11.50        12.35
 14        22.29         5.00         2.76        12.87        13.82
```

```
Uncertainty analysis done on file:          S38V3

Uncertainty in coolant temperatures:        0.050 (degC)
Uncertainty in steam temperature:           0.200 (degC)
Uncertainty in tube thermal conductivity:   1.000 (W/m-K)
Uncertainty in flowmeter reading:           0.500 (pct flow)

Uncertainty in Ci:                          3.22  (pct)
Uncertainty in Alp:                         2.27  (pct)
Uncertainty in Enhancement (const flux):    3.60  (pct)
Uncertainty in Enhancement (const DelT):    2.85  (pct)

          Uncertainty  Uncertainty  Uncertainty  Uncertainty  Uncertainty
            Overall      Outside      Inside        Heat         Film
             H.T.C.       H.T.C.       H.T.C.       Flux        DeltaT
             (pct)        (pct)        (pct)        (pct)        (pct)

  1          21.99         2.31         3.28        12.70         1.83
  2          19.56         4.46         3.30        11.30        12.23
  3          17.33         3.93         3.32        10.02        10.89
  4          15.03         3.51         3.37         8.71         9.57
  5          12.82         3.19         3.45         7.46         8.39
  6          10.38         2.93         3.60         6.11         7.17
  7           8.23         2.79         3.99         5.09         6.42
  8           8.22         2.77         3.99         5.08         6.25
  9          10.51         2.94         3.60         6.19         7.26
 10          12.81         3.18         3.45         7.45         8.39
 11          15.08         3.51         3.37         8.73         9.62
 12          17.25         3.94         3.32         9.97        10.89
 13          19.58         4.49         3.30        11.31        12.30
 14          22.07         4.83         3.28        12.75        13.08
```

```
Uncertainty analysis done on file:            S48V1

Uncertainty in coolant temperatures:          0.050 (degC)
Uncertainty in steam temperature:             0.200 (degC)
Uncertainty in tube thermal conductivity:     1.000 (W/m-K)
Uncertainty in flowmeter reading:             0.500 (pct flow)

Uncertainty in Ci:                            3.67  (pct)
Uncertainty in Alp:                           2.52  (pct)
Uncertainty in Enhancement (const flux):      4.08  (pct)
Uncertainty in Enhancement (const DelT):      3.06  (pct)

          Uncertainty  Uncertainty  Uncertainty  Uncertainty  Uncertainty
            Overall      Outside      Inside        Heat         Film
            H.T.C.       H.T.C.       H.T.C.        Flux        DeltaT
            (pct)        (pct)        (pct)        (pct)        (pct)

  1         21.85         5.56         3.63        12.62        13.75
  2         19.81         4.84         3.64        11.44        12.46
  3         17.45         4.24         3.67        10.09        11.09
  4         15.28         3.77         3.71         8.85         9.81
  5         12.96         3.42         3.78         7.53         8.53
  6         10.65         3.17         3.92         6.27         7.38
  7          8.36         3.02         4.28         5.16         6.53
  8          8.35         2.81         4.28         5.15         2.65
  9         10.74         3.18         3.92         6.32         7.44
 10         12.90         3.41         3.78         7.50         8.49
 11         15.31         3.77         3.71         8.87         9.83
 12         17.74         4.24         3.67        10.25        11.25
 13         20.10         4.81         3.64        11.61        12.61
 14         22.43         5.61         3.63        12.85        14.20
```

```
Uncertainty analysis done on file:            S48V2

Uncertainty in coolant temperatures:          0.050 (degC)
Uncertainty in steam temperature:             0.200 (degC)
Uncertainty in tube thermal conductivity:     1.000 (W/m-K)
Uncertainty in flowmeter reading:             0.500 (pct flow)

Uncertainty in Ci:                            2.09  (pct)
Uncertainty in Alp:                           1.53  (pct)
Uncertainty in Enhancement (const flux):      3.06  (pct)
Uncertainty in Enhancement (const DelT):      2.31  (pct)

          Uncertainty  Uncertainty  Uncertainty  Uncertainty  Uncertainty
            Overall      Outside      Inside        Heat         Film
             H.T.C.       H.T.C.       H.T.C.       Flux        DeltaT
             (pct)        (pct)        (pct)        (pct)        (pct)

 1           21.77         4.89         2.19        12.57        13.49
 2           19.44         4.16         2.21        11.23        12.04
 3           17.33         3.57         2.25        10.02        10.80
 4           15.03         3.06         2.32         8.70         9.43
 5           12.72         2.66         2.43         7.40         8.14
 6           10.43         2.37         2.65         6.14         6.97
 7            8.32         2.20         3.16         5.13         6.21
 8            8.26         1.67         3.16         5.10         2.70
 9           10.51         2.37         2.65         6.19         7.03
10           12.68         2.66         2.43         7.38         8.12
11           15.07         3.06         2.32         8.73         9.46
12           17.33         3.56         2.25        10.02        10.79
13           19.57         4.14         2.21        11.31        12.10
14           22.05         4.88         2.19        12.74        13.64
```

```
Uncertainty analysis done on file:          S75V1

Uncertainty in coolant temperatures:        0.050 (degC)
Uncertainty in steam temperature:           0.200 (degC)
Uncertainty in tube thermal conductivity:   1.000 (W/m-K)
Uncertainty in flowmeter reading:           0.500 (pct flow)

Uncertainty in Ci:                          1.97  (pct)
Uncertainty in Alp:                         1.36  (pct)
Uncertainty in Enhancement (const flux):    2.83  (pct)
Uncertainty in Enhancement (const DelT):    2.20  (pct)

         Uncertainty  Uncertainty  Uncertainty  Uncertainty  Uncertainty
           Overall      Outside      Inside        Heat         Film
           H.T.C.       H.T.C.       H.T.C.        Flux        DeltaT
           (pct)        (pct)        (pct)        (pct)        (pct)

  1        24.41         5.59         2.07        14.10        15.11
  2        21.74         4.71         2.10        12.56        13.53
  3        19.28         3.91         2.14        11.14        11.96
  4        16.67         3.27         2.21         9.65        10.37
  5        14.19         2.78         2.32         8.24         8.95
  6        11.66         2.40         2.55         6.84         7.62
  7         9.15         2.15         3.08         5.58         6.58
  8         9.18         2.12         3.08         5.60         6.42
  9        11.63         2.40         2.56         6.82         7.60
 10        14.22         2.78         2.32         8.26         8.97
 11        16.82         3.28         2.21         9.73        10.46
 12        19.35         3.91         2.14        11.18        11.99
 13        21.94         4.69         2.10        12.67        13.62
 14        24.71         5.66         2.07        14.27        15.42
```

```
Uncertainty analysis done on file:            S75V2

Uncertainty in coolant temperatures:          0.050 (degC)
Uncertainty in steam temperature:             0.200 (degC)
Uncertainty in tube thermal conductivity:     1.000 (W/m-K)
Uncertainty in flowmeter reading:             0.500 (pct flow)

Uncertainty in Ci:                            2.21  (pct)
Uncertainty in Alp:                           1.58  (pct)
Uncertainty in Enhancement (const flux):      3.12  (pct)
Uncertainty in Enhancement (const DelT):      2.34  (pct)

       Uncertainty  Uncertainty  Uncertainty  Uncertainty  Uncertainty
         Overall      Outside      Inside        Heat         Film
         H.T.C.       H.T.C.       H.T.C.        Flux        DeltaT
         (pct)        (pct)        (pct)        (pct)        (pct)

 1       25.47         1.64         2.30        14.71         1.77
 2       22.59         5.05         2.33        13.05        14.00
 3       19.96         4.22         2.37        11.54        12.42
 4       17.41         3.53         2.43        10.07        10.85
 5       14.60         2.98         2.54         8.47         9.22
 6       12.05         2.59         2.74         7.06         7.87
 7        9.45         2.34         3.24         5.75         6.76
 8        9.46         1.72         3.24         5.75         2.69
 9       12.03         2.59         2.74         7.05         7.86
10       14.68         2.98         2.54         8.52         9.27
11       17.18         3.51         2.43         9.94        10.71
12       19.79         4.20         2.37        11.44        12.31
13       22.57         5.02         2.33        13.04        13.98
14       25.21         6.05         2.30        14.56        15.67
```

```
Uncertainty analysis done on file:            S95V1

Uncertainty in coolant temperatures:          0.050 (degC)
Uncertainty in steam temperature:             0.200 (degC)
Uncertainty in tube thermal conductivity:     1.000 (W/m-K)
Uncertainty in flowmeter reading:             0.500 (pct flow)

Uncertainty in Ci:                            3.35  (pct)
Uncertainty in Alp:                           2.24  (pct)
Uncertainty in Enhancement (const flux):      3.77  (pct)
Uncertainty in Enhancement (const DelT):      2.83  (pct)

        Uncertainty  Uncertainty  Uncertainty  Uncertainty  Uncertainty
          Overall      Outside      Inside        Heat         Film
          H.T.C.       H.T.C.       H.T.C.        Flux        DeltaT
          (pct)        (pct)        (pct)        (pct)        (pct)

 1        27.06         7.34         3.40        16.63        17.27
 2        24.25         6.02         3.42        14.01        15.33
 3        21.55         4.98         3.45        12.45        13.53
 4        18.41         4.17         3.49        10.65        11.59
 5        15.89         3.60         3.57         9.22        10.11
 6        12.92         3.17         3.72         7.56         8.50
 7        10.10         2.91         4.10         6.10         7.26
 8        10.18         2.88         4.10         6.15         7.10
 9        12.88         3.16         3.72         7.53         8.48
10        15.96         3.60         3.57         9.25        10.14
11        18.92         4.18         3.49        10.94        11.87
12        21.83         4.91         3.45        12.61        13.58
13        24.94         5.67         3.42        14.41        15.52
14        28.00         7.05         3.40        16.17        17.49
```

```
Uncertainty analysis done on file:                  S95V2

Uncertainty in coolant temperatures:                0.050 (degC)
Uncertainty in steam temperature:                   0.200 (degC)
Uncertainty in tube thermal conductivity:           1.000 (W/m-K)
Uncertainty in flowmeter reading:                   0.500 (pct flow)

Uncertainty in Ci:                                  1.32  (pct)
Uncertainty in Alp:                                  .92  (pct)
Uncertainty in Enhancement (const flux):            2.61  (pct)
Uncertainty in Enhancement (const DelT):            1.96  (pct)

         Uncertainty   Uncertainty   Uncertainty   Uncertainty   Uncertainty
           Overall       Outside       Inside         Heat          Film
           H.T.C.        H.T.C.        H.T.C.         Flux         DeltaT
           (pct)         (pct)         (pct)          (pct)         (pct)

  1        25.67          5.95          1.47          14.82         15.89
  2        23.04          4.95          1.51          13.31         14.30
  3        20.33          4.01          1.57          11.75         12.50
  4        17.54          3.29          1.66          10.15         10.85
  5        14.92          2.70          1.81           8.66          9.31
  6        12.25          2.25          2.09           7.17          7.87
  7         9.63          1.94          2.71           5.85          6.74
  8         9.60          1.89          2.71           5.83          6.54
  9        12.23          2.24          2.09           7.16          7.86
 10        14.79          2.68          1.81           8.59          9.23
 11        17.65          3.29          1.66          10.21         10.91
 12        20.33          4.03          1.57          11.75         12.55
 13        23.07          4.88          1.51          13.32         14.19
 14        25.79          5.93          1.47          14.89         15.94
```

```
Uncertainty analysis done on file:            S126V1

Uncertainty in coolant temperatures:          0.050 (degC)
Uncertainty in steam temperature:             0.200 (degC)
Uncertainty in tube thermal conductivity:     1.000 (W/m-K)
Uncertainty in flowmeter reading:             0.500 (pct flow)

Uncertainty in Ci:                            2.72  (pct)
Uncertainty in Alp:                           1.83  (pct)
Uncertainty in Enhancement (const flux):      3.36  (pct)
Uncertainty in Enhancement (const DelT):      2.52  (pct)

        Uncertainty  Uncertainty  Uncertainty  Uncertainty  Uncertainty
          Overall      Outside      Inside        Heat         Film
          H.T.C.       H.T.C.       H.T.C.        Flux        DeltaT
          (pct)        (pct)        (pct)        (pct)        (pct)

   1      28.50         7.37         2.80        16.46        17.83
   2      25.77         6.12         2.82        14.88        16.17
   3      22.79         5.00         2.85        13.16        14.20
   4      19.56         4.10         2.90        11.31        12.19
   5      16.60         3.44         2.99         9.63        10.44
   6      13.90         2.85         3.17         7.94         8.79
   7      10.54         2.63         3.61         6.35         7.37
   8      10.52         1.95         3.61         6.34         2.69
   9      13.51         2.94         3.17         7.89         8.73
  10      16.42         3.42         2.99         9.52        10.32
  11      19.42         4.09         2.90        11.23        12.10
  12      22.44         4.97         2.85        12.96        13.99
  13      25.45         6.11         2.82        14.70        15.98
  14      28.56         7.34         2.80        16.49        17.86
```

```
Uncertainty analysis done on file:          S126V2

Uncertainty in coolant temperatures:        0.050 (degC)
Uncertainty in steam temperature:           0.200 (degC)
Uncertainty in tube thermal conductivity:   1.000 (W/m-K)
Uncertainty in flowmeter reading:           0.500 (pct flow)

Uncertainty in Ci:                          1.67  (pct)
Uncertainty in Alp:                         1.10  (pct)
Uncertainty in Enhancement (const flux):    2.73  (pct)
Uncertainty in Enhancement (const DelT):    2.05  (pct)

       Uncertainty  Uncertainty  Uncertainty  Uncertainty  Uncertainty
         Overall      Outside      Inside        Heat         Film
         H.T.C.       H.T.C.       H.T.C.        Flux        DeltaT
         (pct)        (pct)        (pct)         (pct)        (pct)

  1      27.55         6.98         1.78         15.91        17.18
  2      24.74         5.87         1.82         14.29        15.32
  3      22.07         4.61         1.87         12.75        13.68
  4      19.07         3.71         1.94         11.03        11.79
  5      16.08         3.00         2.07          9.33        10.01
  6      13.10         2.46         2.33          7.66         8.36
  7      10.26         2.11         2.89          6.19         7.06
  8      10.25         1.29         2.89          6.19         2.65
  9      13.16         2.47         2.33          7.69         8.39
 10      16.15         3.00         2.07          9.36        10.05
 11      18.99         3.69         1.94         10.99        11.74
 12      22.05         4.59         1.87         12.74        13.65
 13      25.01         5.72         1.82         14.45        15.61
 14      28.00         6.94         1.78         16.17        17.42
```

```
Uncertainty analysis done on file:             S142V3

Uncertainty in coolant temperatures:           0.050 (degC)
Uncertainty in steam temperature:              0.200 (degC)
Uncertainty in tube thermal conductivity:      1.000 (W/m-K)
Uncertainty in flowmeter reading:              0.500 (pct flow)

Uncertainty in Ci:                             1.70  (pct)
Uncertainty in Alp:                            1.01  (pct)
Uncertainty in Enhancement (const flux):       2.67  (pct)
Uncertainty in Enhancement (const DelT):       2.00  (pct)

      Uncertainty  Uncertainty  Uncertainty  Uncertainty  Uncertainty
        Overall      Outside       Inside        Heat         Film
        H.T.C.       H.T.C.        H.T.C.        Flux        DeltaT
        (pct)        (pct)         (pct)         (pct)       (pct)

 1      27.76         8.30         1.81         16.03        17.64
 2      24.66         6.54         1.84         14.24        15.48
 3      21.77         5.15         1.89         12.58        13.67
 4      18.61         3.97         1.97         10.77        11.59
 5      15.87         3.09         2.10          9.20         9.88
 6      12.83         2.44         2.35          7.51         8.14
 7      10.05         2.03         2.91          6.08         6.82
 8      10.03         1.17         2.91          6.07         2.32
 9      12.80         2.43         2.35          7.49         8.12
10      15.69         3.07         2.10          9.10         9.77
11      18.60         3.96         1.97         10.76        11.57
12      21.53         5.16         1.89         12.44        13.53
13      24.62         6.49         1.84         14.22        15.43
14      27.39         8.74         1.81         15.81        17.92
```

```
Uncertainty analysis done on file:            S142V4

Uncertainty in coolant temperatures:          0.050 (degC)
Uncertainty in steam temperature:             0.200 (degC)
Uncertainty in tube thermal conductivity:     1.000 (W/m-K)
Uncertainty in flowmeter reading:             0.500 (pct flow)

Uncertainty in Ci:                            2.82  (pct)
Uncertainty in Alp:                           1.79  (pct)
Uncertainty in Enhancement (const flux):      3.32  (pct)
Uncertainty in Enhancement (const DelT):      2.49  (pct)

        Uncertainty  Uncertainty  Uncertainty  Uncertainty  Uncertainty
          Overall      Outside      Inside        Heat         Film
          H.T.C.       H.T.C.       H.T.C.        Flux        DeltaT
          (pct)        (pct)        (pct)        (pct)        (pct)

 1        27.29         8.08         2.89        15.76        17.35
 2        24.26         6.46         2.91        14.01        15.27
 3        21.52         5.21         2.94        12.44        13.57
 4        18.43         4.14         2.99        10.66        11.50
 5        15.50         3.39         3.08         8.99         9.78
 6        12.77         2.87         3.25         7.47         8.26
 7         9.92         2.53         3.68         6.01         6.93
 8         9.97         2.60         3.68         6.04         6.76
 9        12.75         2.86         3.25         7.46         8.25
10        15.49         3.38         3.08         8.99         9.77
11        18.42         4.15         2.99        10.66        11.56
12        21.23         5.21         2.94        12.27        13.40
13        23.86         6.67         2.91        13.78        15.30
14        27.16         7.06         2.89        15.68        15.87
```

```
Uncertainty analysis done on file:              S142V5

Uncertainty in coolant temperatures:            0.050 (degC)
Uncertainty in steam temperature:               0.200 (degC)
Uncertainty in tube thermal conductivity:       1.000 (W/m-K)
Uncertainty in flowmeter reading:               0.500 (pct flow)

Uncertainty in Ci:                              4.87  (pct)
Uncertainty in Alp:                             2.86  (pct)
Uncertainty in Enhancement (const flux):        4.57  (pct)
Uncertainty in Enhancement (const DelT):        3.43  (pct)

          Uncertainty  Uncertainty  Uncertainty  Uncertainty  Uncertainty
            Overall      Outside      Inside        Heat         Film
            H.T.C.       H.T.C.       H.T.C.        Flux        DeltaT
            (pct)        (pct)        (pct)        (pct)        (pct)

 1          28.19         9.05         4.91        16.28        18.58
 2          25.22         7.12         4.92        14.57        16.04
 3          22.18         5.93         4.94        12.81        14.20
 4          18.91         4.93         4.97        10.94        12.05
 5          15.85         4.26         5.02         9.20        10.30
 6          12.96         3.80         5.13         7.58         8.72
 7           9.99         3.52         5.41         6.05         7.38
 8           9.97         3.02         5.41         6.03         2.33
 9          12.71         3.79         5.13         7.44         8.58
10          15.76         4.25         5.02         9.14        10.24
11          18.50         4.96         4.97        10.70        11.90
12          21.27         6.00         4.94        12.29        13.73
13          24.24         7.47         4.92        14.00        15.84
14          27.28         8.94         4.91        15.75        17.63
```

```
Uncertainty analysis done on file:             SSMTA2

Uncertainty in coolant temperatures:           0.050 (degC)
Uncertainty in steam temperature:              0.400 (degC)
Uncertainty in tube thermal conductivity:      1.000 (W/m-K)
Uncertainty in flowmeter reading:              0.500 (pct flow)

Uncertainty in Ci:                             3.96  (pct)
Uncertainty in Alp:                            1.69  (pct)

        Uncertainty  Uncertainty  Uncertainty  Uncertainty  Uncertainty
          Overall      Outside      Inside        Heat         Film
          H.T.C.       H.T.C.       H.T.C.        Flux        DeltaT
          (pct)        (pct)        (pct)        (pct)        (pct)

  1        9.22        12.51         4.00         5.34         9.44
  2        8.23         7.91         4.01         4.78         7.60
  3        7.15         5.29         4.04         4.17         6.15
  4        6.27         3.68         4.07         3.69         5.24
  5        5.32         2.71         4.14         3.21         4.37
  6        4.43         2.29         4.27         2.84         3.89
  7        3.84         2.16         4.60         2.87         3.89
  8        3.83         1.73         4.60         2.87         1.49
  9        4.42         2.29         4.27         2.84         3.87
 10        5.29         2.71         4.14         3.19         4.34
 11        6.27         3.58         4.07         3.69         5.17
 12        7.22         5.68         4.04         4.21         6.55
 13        8.22         7.52         4.01         4.77         7.43
 14        9.29        11.78         4.00         5.38         9.28
```

Uncertainty analysis done on file: SSMTA3

Uncertainty in coolant temperatures: 0.050 (degC)
Uncertainty in steam temperature: 0.400 (degC)
Uncertainty in tube thermal conductivity: 1.000 (W/m-K)
Uncertainty in flowmeter reading: 0.500 (pct flow)

Uncertainty in Ci: 2.67 (pct)
Uncertainty in Alp: 1.14 (pct)

	Uncertainty Overall H.T.C. (pct)	Uncertainty Outside H.T.C. (pct)	Uncertainty Inside H.T.C. (pct)	Uncertainty Heat Flux (pct)	Uncertainty Film DeltaT (pct)
1	9.37	6.82	2.74	5.43	7.12
2	8.33	6.48	2.77	4.84	7.07
3	7.27	4.30	2.80	4.24	5.75
4	6.29	3.04	2.85	3.70	4.87
5	5.32	2.18	2.94	3.21	4.07
6	4.44	1.78	3.12	2.85	3.61
7	3.87	1.65	3.57	2.89	3.66
8	3.85	1.20	3.57	2.88	1.51
9	4.43	1.77	3.12	2.84	3.60
10	5.33	2.16	2.94	3.21	4.05
11	6.30	2.96	2.85	3.71	4.83
12	7.29	4.72	2.80	4.25	6.07
13	8.26	6.66	2.77	4.79	7.02
14	9.34	10.29	2.74	5.41	8.77

```
Uncertainty analysis done on file:            S16A1

Uncertainty in coolant temperatures:          0.050 (degC)
Uncertainty in steam temperature:             0.400 (degC)
Uncertainty in tube thermal conductivity:     1.000 (W/m-K)
Uncertainty in flowmeter reading:             0.500 (pct flow)

Uncertainty in Ci:                            3.43  (pct)
Uncertainty in Alp:                           2.01  (pct)
Uncertainty in Enhancement (const flux):      2.94  (pct)
Uncertainty in Enhancement (const DelT):      2.21  (pct)

      Uncertainty  Uncertainty  Uncertainty  Uncertainty  Uncertainty
        Overall      Outside      Inside        Heat         Film
        H.T.C.       H.T.C.       H.T.C.        Flux        DeltaT
        (pct)        (pct)        (pct)        (pct)        (pct)

 1       7.68         3.77         3.49         4.45         5.67
 2       6.87         3.39         3.50         4.00         5.33
 3       6.10         2.91         3.53         3.57         4.78
 4       5.28         2.62         3.57         3.14         4.32
 5       4.57         2.43         3.64         2.80         4.01
 6       3.87         2.34         3.79         2.56         3.83
 7       3.52         2.32         4.16         2.74         4.05
 8       3.52         2.06         4.16         2.74         1.87
 9       3.87         2.34         3.79         2.56         3.83
10       4.51         2.44         3.64         2.77         3.98
11       5.29         2.61         3.57         3.14         4.31
12       6.06         2.91         3.53         3.55         4.75
13       6.87         3.36         3.50         3.99         5.30
14       7.75         3.72         3.49         4.49         5.70
```

```
Uncertainty analysis done on file:              S16A2

Uncertainty in coolant temperatures:            0.050 (degC)
Uncertainty in steam temperature:               0.400 (degC)
Uncertainty in tube thermal conductivity:       1.000 (W/m-K)
Uncertainty in flowmeter reading:               0.500 (pct flow)

Uncertainty in Ci:                              3.85  (pct)
Uncertainty in Alp:                             2.33  (pct)
Uncertainty in Enhancement (const flux):        3.34  (pct)
Uncertainty in Enhancement (const DelT):        2.50  (pct)

        Uncertainty  Uncertainty  Uncertainty  Uncertainty  Uncertainty
          Overall      Outside      Inside        Heat         Film
          H.T.C.       H.T.C.       H.T.C.        Flux        DeltaT
          (pct)        (pct)        (pct)         (pct)        (pct)

 1         7.80         4.15         3.90         4.52         6.15
 2         6.96         3.57         3.92         4.05         5.50
 3         6.15         3.18         3.94         3.60         4.98
 4         5.32         2.92         3.98         3.16         4.53
 5         4.56         2.74         4.04         2.79         4.21
 6         3.88         2.65         4.18         2.56         4.04
 7         3.54         2.63         4.52         2.74         4.26
 8         3.54         2.38         4.52         2.74         1.93
 9         3.89         2.65         4.18         2.57         4.05
10         4.56         2.74         4.04         2.79         4.20
11         5.26         2.93         3.98         3.12         4.51
12         6.03         3.21         3.94         3.53         4.92
13         6.91         3.47         3.92         4.02         5.31
14         7.67         4.24         3.90         4.45         6.10
```

```
Uncertainty analysis done on file:               S28A1

Uncertainty in coolant temperatures:             0.050 (degC)
Uncertainty in steam temperature:                0.400 (degC)
Uncertainty in tube thermal conductivity:        1.000 (W/m-K)
Uncertainty in flowmeter reading:                0.500 (pct flow)

Uncertainty in Ci:                               2.68  (pct)
Uncertainty in Alp:                              2.01  (pct)
Uncertainty in Enhancement (const flux):         2.85  (pct)
Uncertainty in Enhancement (const DelT):         2.21  (pct)

          Uncertainty  Uncertainty  Uncertainty  Uncertainty  Uncertainty
            Overall      Outside      Inside        Heat         Film
            H.T.C.       H.T.C.       H.T.C.        Flux        DeltaT
            (pct)        (pct)        (pct)        (pct)        (pct)

  1          6.97         2.92         2.76         4.05         5.11
  2          6.27         2.70         2.78         3.66         4.73
  3          5.57         2.54         2.81         3.27         4.42
  4          4.88         2.41         2.86         2.91         4.12
  5          4.22         2.33         2.95         2.61         3.91
  6          3.64         2.29         3.13         2.44         3.86
  7          3.41         2.31         3.57         2.69         4.19
  8          3.41         2.29         3.57         2.69         4.08
  9          3.66         2.29         3.13         2.45         3.87
 10          4.20         2.33         2.95         2.59         3.89
 11          4.89         2.41         2.86         2.92         4.12
 12          5.54         2.54         2.81         3.25         4.40
 13          6.30         2.71         2.79         3.67         4.79
 14          7.06         2.91         2.76         4.10         5.15
```

```
Uncertainty analysis done on file:                 S28A2

Uncertainty in coolant temperatures:               0.050 (degC)
Uncertainty in steam temperature:                  0.400 (degC)
Uncertainty in tube thermal conductivity:          1.000 (W/m-K)
Uncertainty in flowmeter reading:                  0.500 (pct flow)

Uncertainty in Ci:                                 4.10  (pct)
Uncertainty in Alp:                                3.09  (pct)
Uncertainty in Enhancement (const flux):           4.30  (pct)
Uncertainty in Enhancement (const DelT):           3.22  (pct)

        Uncertainty  Uncertainty  Uncertainty  Uncertainty  Uncertainty
          Overall      Outside      Inside        Heat         Film
          H.T.C.       H.T.C.       H.T.C.        Flux        DeltaT
          (pct)        (pct)        (pct)        (pct)        (pct)

  1        7.21         3.89         4.15         4.18         5.42
  2        6.46         3.93         4.17         3.76         5.61
  3        5.73         3.70         4.19         3.36         5.22
  4        5.03         3.54         4.22         2.99         4.91
  5        4.36         3.44         4.28         2.68         4.70
  6        3.75         3.38         4.41         2.50         4.62
  7        3.47         3.37         4.74         2.71         4.86
  8        3.46         3.37         4.74         2.71         4.84
  9        3.75         3.38         4.41         2.50         4.62
 10        4.32         3.44         4.28         2.66         4.68
 11        5.00         3.54         4.22         2.98         4.89
 12        5.68         3.71         4.19         3.33         5.19
 13        6.47         3.86         4.17         3.77         5.50
 14        7.22         4.21         4.15         4.19         6.05
```

```
Uncertainty analysis done on file:              S28A3

Uncertainty in coolant temperatures:            0.050 (degC)
Uncertainty in steam temperature:               0.400 (degC)
Uncertainty in tube thermal conductivity:       1.000 (W/m-K)
Uncertainty in flowmeter reading:               0.500 (pct flow)

Uncertainty in Ci:                              3.29  (pct)
Uncertainty in Alp:                             2.37  (pct)
Uncertainty in Enhancement (const flux):        3.39  (pct)
Uncertainty in Enhancement (const DelT):        2.54  (pct)

          Uncertainty  Uncertainty  Uncertainty  Uncertainty  Uncertainty
            Overall      Outside       Inside        Heat         Film
             H.T.C.       H.T.C.       H.T.C.        Flux        DeltaT
             (pct)        (pct)        (pct)        (pct)        (pct)

 1           7.27         3.44         3.35         4.21         5.49
 2           6.53         3.19         3.36         3.80         5.16
 3           5.77         2.97         3.39         3.38         4.74
 4           5.00         2.81         3,43         2.98         4.38
 5           4.34         2.71         3.51         2.67         4.16
 6           3.74         2.65         3.66         2.49         4.08
 7           3.46         2.66         4,05         2.71         4.36
 8           3.46         2.43         4.05         2.71         2.15
 9           3.74         2.65         3,66         2.49         4.09
10           4.33         2.71         3,51         2.66         4.15
11           5.01         2.81         3.43         2.98         4.38
12           5.72         2.97         3.39         3.35         4.71
13           6.49         3.20         3,36         3.78         5.13
14           7.22         3.53         3.35         4.19         5.60
```

```
Uncertainty analysis done on file:          S38A1

Uncertainty in coolant temperatures:        0.050 (degC)
Uncertainty in steam temperature:           0.400 (degC)
Uncertainty in tube thermal conductivity:   1.000 (W/m-K)
Uncertainty in flowmeter reading:           0.500 (pct flow)

Uncertainty in Ci:                          2.83  (pct)
Uncertainty in Alp:                         1.80  (pct)
Uncertainty in Enhancement (const flux):    2.69  (pct)
Uncertainty in Enhancement (const DelT):    2.02  (pct)

        Uncertainty  Uncertainty  Uncertainty  Uncertainty  Uncertainty
          Overall      Outside      Inside        Heat         Film
          H.T.C.       H.T.C.       H.T.C.        Flux        DeltaT
          (pct)        (pct)        (pct)        (pct)        (pct)

 1        8.20         3.44         2.95         4.75         5.81
 2        7.29         3.05         2.97         4.23         5.37
 3        6.43         2.65         3.00         3.76         4.81
 4        5.58         2.39         3.04         3.30         4.34
 5        4.79         2.22         3.13         2.92         4.00
 6        4.06         2.13         3.30         2.65         3.82
 7        3.65         2.12         3.72         2.78         4.04
 8        3.65         1.87         3.72         2.79         2.01
 9        4.07         2.13         3.30         2.66         3.83
10        4.79         2.22         3.13         2.92         4.00
11        5.55         2.38         3.04         3.29         4.32
12        6.40         2.65         3.00         3.74         4.79
13        7.30         3.04         2.97         4.24         5.36
14        8.15         3.59         2.95         4.72         5.99
```

```
Uncertainty analysis done on file:          538A2

Uncertainty in coolant temperatures:        0.050 (degC)
Uncertainty in steam temperature:           0.400 (degC)
Uncertainty in tube thermal conductivity:   1.000 (W/m-K)
Uncertainty in flowmeter reading:           0.500 (pct flow)

Uncertainty in Ci:                          1.84  (pct)
Uncertainty in Alp:                         1.21  (pct)
Uncertainty in Enhancement (const flux):    2.03  (pct)
Uncertainty in Enhancement (const DelT):    1.62  (pct)

        Uncertainty  Uncertainty  Uncertainty  Uncertainty  Uncertainty
          Overall      Outside      Inside        Heat         Film
          H.T.C.       H.T.C.       H.T.C.        Flux        DeltaT
          (pct)        (pct)        (pct)         (pct)        (pct)

  1        7.99         2.81         1.94         4.63         5.44
  2        7.18         2.44         1.97         4.17         5.02
  3        6.34         2.08         2.02         3.71         4.49
  4        5.50         1.82         2.09         3.26         4.04
  5        4.72         1.66         2.21         2.88         3.71
  6        4.03         1.58         2.45         2.64         3.56
  7        3.64         1.59         2.99         2.79         3.82
  8        3.64         1.57         2.99         2.79         3.72
  9        4.04         1.58         2.45         2.64         3.57
 10        4.74         1.66         2.21         2.89         3.72
 11        5.51         1.82         2.09         3.26         4.04
 12        6.36         2.06         2.02         3.72         4.50
 13        7.19         2.42         1.97         4.18         5.02
 14        8.09         2.78         1.94         4.69         5.49
```

```
Uncertainty analysis done on file:          S48A1

Uncertainty in coolant temperatures:        0.050 (degC)
Uncertainty in steam temperature:           0.400 (degC)
Uncertainty in tube thermal conductivity:   1.000 (W/m-K)
Uncertainty in flowmeter reading:           0.500 (pct flow)

Uncertainty in Ci:                          2.69  (pct)
Uncertainty in Alp:                         1.78  (pct)
Uncertainty in Enhancement (const flux):    2.67  (pct)
Uncertainty in Enhancement (const DelT):    2.00  (pct)

          Uncertainty  Uncertainty  Uncertainty  Uncertainty  Uncertainty
            Overall      Outside      Inside        Heat         Film
            H.T.C.       H.T.C.       H.T.C.        Flux        DeltaT
            (pct)        (pct)        (pct)        (pct)        (pct)

 1          7.98         3.35         2.76         4.62         5.67
 2          7.12         2.92         2.79         4.14         5.13
 3          6.31         2.60         2.82         3.69         4.73
 4          5.52         2.34         2.87         3.27         4.30
 5          4.75         2.19         2.96         2.89         3.97
 6          4.03         2.10         3.14         2.64         3.81
 7          3.64         2.10         3.58         2.79         4.04
 8          3.64         1.85         3.58         2.79         2.04
 9          4.04         2.10         3.14         2.64         3.82
10          4.72         2.18         2.96         2.88         3.96
11          5.52         2.34         2.87         3.27         4.29
12          6.30         2.59         2.82         3.68         4.71
13          7.15         2.96         2.79         4.16         5.25
14          8.02         3.47         2.76         4.65         5.87
```

```
Uncertainty analysis done on file:           S48A2

Uncertainty in coolant temperatures:         0.050 (degC)
Uncertainty in steam temperature:            0.400 (degC)
Uncertainty in tube thermal conductivity:    1.000 (W/m-K)
Uncertainty in flowmeter reading:            0.500 (pct flow)

Uncertainty in Ci:                           2.04  (pct)
Uncertainty in Alp:                          1.42  (pct)
Uncertainty in Enhancement (const flux):     2.25  (pct)
Uncertainty in Enhancement (const DelT):     1.69  (pct)

      Uncertainty  Uncertainty  Uncertainty  Uncertainty  Uncertainty
        Overall      Outside      Inside        Heat         Film
        H.T.C.       H.T.C.       H.T.C.        Flux        DeltaT
        (pct)        (pct)        (pct)        (pct)        (pct)

 1       7.85         2.90         2.13         4.55         5.42
 2       7.02         2.50         2.16         4.08         4.91
 3       6.21         2.21         2.20         3.63         4.49
 4       5.44         1.98         2.27         3.22         4.09
 5       4.66         1.83         2.38         2.85         3.76
 6       4.00         1.76         2.60         2.62         3.64
 7       3.61         1.77         3.12         2.78         3.90
 8       3.62         1.51         3.12         2.78         2.11
 9       3.98         1.75         2.60         2.61         3.63
10       4.69         1.83         2.38         2.86         3.78
11       5.41         1.97         2.27         3.21         4.06
12       6.24         2.20         2.20         3.65         4.50
13       7.07         2.53         2.16         4.11         5.01
14       7.93         2.87         2.13         4.59         5.46
```

```
Uncertainty analysis done on file:            S75A1

Uncertainty in coolant temperatures:          0.050 (degC)
Uncertainty in steam temperature:             0.400 (degC)
Uncertainty in tube thermal conductivity:     1.000 (W/m-K)
Uncertainty in flowmeter reading:             0.500 (pct flow)

Uncertainty in Ci:                            2.44  (pct)
Uncertainty in Alp:                           1.61  (pct)
Uncertainty in Enhancement (const flux):      2.48  (pct)
Uncertainty in Enhancement (const DelT):      1.86  (pct)

        Uncertainty  Uncertainty  Uncertainty  Uncertainty  Uncertainty
          Overall      Outside      Inside        Heat         Film
          H.T.C.       H.T.C.       H.T.C.        Flux        DeltaT
          (pct)        (pct)        (pct)        (pct)        (pct)

  1        8.58         3.48         2.62         4.87         5.99
  2        7.68         2.96         2.55         4.46         5.40
  3        6.77         2.58         2.58         3.95         4.92
  4        5.89         2.27         2.64         3.48         4.42
  5        5.10         2.07         2.74         3.08         4.06
  6        4.30         1.87         2.93         2.77         3.84
  7        3.80         1.95         3.40         2.86         4.02
  8        3.81         1.69         3.40         2.86         2.04
  9        4.31         1.97         2.93         2.78         3.85
 10        5.09         2.07         2.74         3.08         4.06
 11        5.90         2.26         2.64         3.48         4.41
 12        6.79         2.56         2.59         3.96         4.92
 13        7.71         3.01         2.55         4.48         5.53
 14        8.60         3.85         2.52         4.98         6.22
```

```
Uncertainty analysis done on file:              S75A2

Uncertainty in coolant temperatures:            0.050 (degC)
Uncertainty in steam temperature:               0.400 (degC)
Uncertainty in tube thermal conductivity:       1.000 (W/m-K)
Uncertainty in flowmeter reading:               0.500 (pct flow)

Uncertainty in Ci:                              2.26  (pct)
Uncertainty in Alp:                             1.51  (pct)
Uncertainty in Enhancement (const flux):        2.36  (pct)
Uncertainty in Enhancement (const DelT):        1.77  (pct)

        Uncertainty  Uncertainty  Uncertainty  Uncertainty  Uncertainty
          Overall      Outside      Inside        Heat         Film
          H.T.C.       H.T.C.       H.T.C.        Flux        DeltaT
          (pct)        (pct)        (pct)         (pct)        (pct)

 1         8.32         3.59         2.36          4.82         6.03
 2         7.47         2.94         2.37          4.34         5.38
 3         6.64         2.47         2.41          3.88         4.80
 4         5.78         2.16         2.47          3.42         4.31
 5         4.99         1.97         2.58          3.02         3.96
 6         4.24         1.87         2.78          2.74         3.77
 7         3.77         1.88         3.27          2.84         3.97
 8         3.76         1.84         3.27          2.84         3.85
 9         4.24         1.87         2.78          2.75         3.77
10         4.98         1.96         2.58          3.02         3.96
11         5.81         2.15         2.47          3.43         4.32
12         6.66         2.45         2.41          3.89         4.80
13         7.62         2.78         2.37          4.43         5.30
14         8.54         3.45         2.35          4.95         6.10
```

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Uncertainty analysis done on file:          S95A1

Uncertainty in coolant temperatures:        0.050 (degC)
Uncertainty in steam temperature:           0.400 (degC)
Uncertainty in tube thermal conductivity:   1.000 (W/m-K)
Uncertainty in flowmeter reading:           0.500 (pct flow)

Uncertainty in Ci:                          2.90  (pct)
Uncertainty in Alp:                         2.00  (pct)
Uncertainty in Enhancement (const flux):    2.93  (pct)
Uncertainty in Enhancement (const DelT):    2.20  (pct)

       Uncertainty  Uncertainty  Uncertainty  Uncertainty  Uncertainty
         Overall      Outside      Inside        Heat         Film
          H.T.C.       H.T.C.       H.T.C.       Flux        DeltaT
          (pct)        (pct)        (pct)        (pct)        (pct)

 1        8.78         3.90         2.87         5.08         6.27
 2        7.84         3.45         2.99         4.55         5.83
 3        6.91         2.97         3.02         4.03         5.19
 4        6.01         2.65         3.07         3.55         4.67
 5        5.19         2.45         3.15         3.14         4.30
 6        4.40         2.34         3.32         2.83         4.09
 7        3.87         2.32         3.74         2.89         4.24
 8        3.87         2.30         3.74         2.89         4.11
 9        4.38         2.34         3.32         2.82         4.08
10        5.19         2.44         3.15         3.14         4.30
11        6.02         2.64         3.07         3.55         4.67
12        6.92         2.96         3.02         4.04         5.18
13        7.83         3.43         2.99         4.55         5.80
14        8.77         4.10         2.97         5.08         6.53
```

```
Uncertainty analysis done on file:            S95A2

Uncertainty in coolant temperatures:          0.050 (degC)
Uncertainty in steam temperature:             0.400 (degC)
Uncertainty in tube thermal conductivity:     1.000 (W/m-K)
Uncertainty in flowmeter reading:             0.500 (pct flow)

Uncertainty in Ci:                            1.90  (pct)
Uncertainty in Alp:                           1.31  (pct)
Uncertainty in Enhancement (const flux):      2.13  (pct)
Uncertainty in Enhancement (const DelT):      1.60  (pct)

       Uncertainty  Uncertainty  Uncertainty  Uncertainty  Uncertainty
         Overall      Outside      Inside        Heat         Film
         H.T.C.       H.T.C.       H.T.C.        Flux        DeltaT
         (pct)        (pct)        (pct)        (pct)        (pct)

 1        8.54         3.23         2.00         4.94         5.85
 2        7.61         2.71         2.03         4.42         5.25
 3        6.72         2.32         2.07         3.92         4.77
 4        5.84         2.00         2.14         3.45         4.26
 5        5.02         1.79         2.26         3.04         3.88
 6        4.28         1.69         2.49         2.77         3.70
 7        3.81         1.69         3.03         2.86         3.92
 8        3.81         1.41         3.03         2.86         2.08
 9        4.29         1.69         2.49         2.77         3.71
10        5.07         1.79         2.26         3.07         3.91
11        5.88         1.98         2.14         3.47         4.28
12        6.79         2.29         2.07         3.96         4.79
13        7.69         2.74         2.03         4.47         5.39
14        8.60         3.37         2.00         4.98         6.08
```

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Uncertainty analysis done on file:          S126A2

Uncertainty in coolant temperatures:        0.050 (degC)
Uncertainty in steam temperature:           0.400 (degC)
Uncertainty in tube thermal conductivity:   1.000 (W/m-K)
Uncertainty in flowmeter reading:           0.500 (pct flow)

Uncertainty in Ci:                          1.66  (pct)
Uncertainty in Alp:                         1.09  (pct)
Uncertainty in Enhancement (const flux):    1.90  (pct)
Uncertainty in Enhancement (const DelT):    1.43  (pct)

        Uncertainty  Uncertainty  Uncertainty  Uncertainty  Uncertainty
          Overall      Outside      Inside        Heat         Film
          H.T.C.       H.T.C.       H.T.C.        Flux        DeltaT
          (pct)        (pct)        (pct)        (pct)        (pct)

 1         9.32         4.39         1.77         5.39         6.80
 2         8.23         3.36         1.81         4.78         5.88
 3         7.33         2.56         1.86         4.27         5.14
 4         6.42         2.05         1.93         3.78         4.53
 5         5.46         1.73         2.07         3.29         4.03
 6         4.62         1.56         2.32         2.94         3.75
 7         4.03         1.53         2.89         2.96         3.89
 8         4.03         1.50         2.89         2.96         3.77
 9         4.64         1.56         2.32         2.95         3.76
10         5.48         1.72         2.07         3.30         4.04
11         6.44         2.04         1.93         3.79         4.55
12         7.40         2.51         1.86         4.31         5.15
13         8.41         3.20         1.81         4.88         5.91
14         9.46         4.18         1.78         5.47         6.80
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Uncertainty analysis done on file:          S125A3

Uncertainty in coolant temperatures:        0.050 (degC)
Uncertainty in steam temperature:           0.400 (degC)
Uncertainty in tube thermal conductivity:   1.000 (W/m-K)
Uncertainty in flowmeter reading:           0.500 (pct flow)

Uncertainty in Ci:                          2.12  (pct)
Uncertainty in Alp:                         1.44  (pct)
Uncertainty in Enhancement (const flux):    2.28  (pct)
Uncertainty in Enhancement (const DelT):    1.71  (pct)

        Uncertainty  Uncertainty  Uncertainty  Uncertainty  Uncertainty
          Overall      Outside      Inside        Heat         Film
          H.T.C.       H.T.C.       H.T.C.        Flux        DeltaT
          (pct)        (pct)        (pct)         (pct)        (pct)

  1        9.09         4.34         2.21         5.26         6.70
  2        8.10         3.40         2.24         4.70         5.87
  3        7.24         2.69         2.28         4.22         5.18
  4        6.29         2.25         2.34         3.70         4.58
  5        5.40         1.98         2.45         3.25         4.13
  6        4.58         1.84         2.67         2.92         3.87
  7        3.98         1.82         3.17         2.94         4.01
  8        3.98         1.53         3.17         2.94         2.02
  9        4.57         1.84         2.67         2.92         3.87
 10        5.39         1.98         2.45         3.24         4.12
 11        6.37         2.23         2.34         3.75         4.61
 12        7.27         2.64         2.28         4.24         5.17
 13        8.27         3.25         2.24         4.80         5.88
 14        9.24         4.13         2.21         5.35         6.71
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Uncertainty analysis done on file:           S142A3

Uncertainty in coolant temperatures:         0.050 (degC)
Uncertainty in steam temperature:            0.400 (degC)
Uncertainty in tube thermal conductivity:    1.000 (W/m-K)
Uncertainty in flowmeter reading:            0.500 (pct flow)

Uncertainty in Ci:                           1.81  (pct)
Uncertainty in Alp:                          1.06  (pct)
Uncertainty in Enhancement (const flux):     1.87  (pct)
Uncertainty in Enhancement (const DelT):     1.40  (pct)

          Uncertainty  Uncertainty  Uncertainty  Uncertainty  Uncertainty
            Overall      Outside      Inside        Heat         Film
            H.T.C.       H.T.C.       H.T.C.        Flux        DeltaT
            (pct)        (pct)        (pct)        (pct)        (pct)

  1          9.46         5.02         1.92         6.48         6.74
  2          8.50         4.31         1.95         4.93         6.38
  3          7.53         3.05         1.99         4.39         5.42
  4          6.52         2.31         2.07         3.83         4.65
  5          5.56         1.84         2.19         3.34         4.08
  6          4.67         1.59         2.43         2.97         3.72
  7          4.04         1.53         2.98         2.97         3.79
  8          4.03         1.49         2.98         2.96         3.66
  9          4.69         1.59         2.43         2.98         3.73
 10          5.60         1.83         2.19         3.36         4.09
 11          6.52         2.30         2.07         3.84         4.66
 12          7.57         3.00         1.99         4.41         5.39
 13          8.62         4.08         1.95         5.00         6.33
 14          9.62         5.83         1.92         5.57         7.48
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Uncertainty analysis done on file:          6142A4

Uncertainty in coolant temperatures:        0.050 (degC)
Uncertainty in steam temperature:           0.400 (degC)
Uncertainty in tube thermal conductivity:   1.000 (W/m-K)
Uncertainty in flowmeter reading:           0.500 (pct flow)

Uncertainty in Ci:                          3.20  (pct)
Uncertainty in Alp:                         1.86  (pct)
Uncertainty in Enhancement (const flux):    2.76  (pct)
Uncertainty in Enhancement (const DelT):    2.07  (pct)

      Uncertainty  Uncertainty  Uncertainty  Uncertainty  Uncertainty
        Overall      Outside      Inside        Heat         Film
        H.T.C.       H.T.C.       H.T.C.        Flux        DeltaT
        (pct)        (pct)        (pct)        (pct)        (pct)

  1      9.36         9.14         3.26         5.42         9.05
  2      8.41         5.13         3.28         4.88         6.76
  3      7.40         3.81         3.31         4.32         5.75
  4      6.44         3.00         3.35         3.79         4.97
  5      5.53         2.54         3.43         3.32         4.42
  6      4.60         2.31         3.59         2.93         4.04
  7      4.01         2.23         3.88         2.95         4.11
  8      4.01         1.91         3.88         2.95         1.78
  9      4.64         2.30         3.59         2.96         4.06
 10      5.52         2.53         3.43         3.32         4.41
 11      6.53         2.92         3.35         3.84         4.97
 12      7.48         3.80         3.31         4.36         5.84
 13      8.61         4.24         3.28         4.99         6.25
 14      9.58         6.47         3.26         5.55         7.82
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Uncertainty analysis done on file:              S142AS

Uncertainty in coolant temperatures:            0.050 (degC)
Uncertainty in steam temperature:               0.400 (degC)
Uncertainty in tube thermal conductivity:       1.000 (W/m-K)
Uncertainty in flowmeter reading:               0.500 (pct flow)

Uncertainty in Ci:                              2.22  (pct)
Uncertainty in Alp:                             1.32  (pct)
Uncertainty in Enhancement (const flux):        2.15  (pct)
Uncertainty in Enhancement (const DelT):        1.61  (pct)

       Uncertainty  Uncertainty  Uncertainty  Uncertainty  Uncertainty
         Overall      Outside      Inside        Heat         Film
         H.T.C.       H.T.C.       H.T.C.        Flux        DeltaT
         (pct)        (pct)        (pct)        (pct)        (pct)

 1        9.34         4.84         2.31         5.41         6.67
 2        8.33         4.16         2.33         4.83         6.26
 3        7.40         3.06         2.37         4.31         5.38
 4        6.40         2.40         2.43         3.77         4.65
 5        5.45         2.00         2.54         3.28         4.11
 6        4.59         1.79         2.75         2.93         3.78
 7        3.98         1.73         3.24         2.94         3.87
 8        3.98         1.40         3.24         2.94         1.82
 9        4.58         1.79         2.75         2.92         3.77
10        5.43         2.00         2.54         3.27         4.10
11        6.42         2.37         2.43         3.78         4.64
12        7.39         3.01         2.37         4.31         5.33
13        8.44         3.94         2.33         4.90         6.22
14        9.36         6.44         2.31         5.42         7.87
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